Symposium

Four decades of data-driven modeling in systems and control – achievements and prospects

Blauwe Zaal Auditorium, Eindhoven University of Technology
Friday, April 19, 2024

Preceding the valedictory lecture of Prof.dr.ir. Paul Van den Hof, you are cordially invited to attend this one-day symposium.

PROGRAM

09:30	**Walk in and coffee**
09:50	**Opening and welcome** Prof.dr. Siep Weiland, group chair Control Systems (CS) at TU/e.
09:55	**Morning session:**

Back to the roots: a spectrum of what was realized
Prof. Bart De Moor, *KU Leuven, Belgium*

If a mathematical operator maps an object onto itself, we call it an eigen-object for that operator. Examples include eigen-functions of a combination of differential or integral operator, or vectors acted upon by a linear transformation. Such objects are mapped onto themselves up to within scalars, called eigenvalues, the set of which is called the (eigen-)spectrum.

Eigen-objects and eigen-spectra appear ubiquitously in science and engineering: in electromagnetism, they provide the fundamental solutions to Maxwell's equations; Heisenberg's matrix mechanics is, in essence, an eigenvalue problem, equivalent to Schrödinger's wave equation, subsequently reconciled with the special theory of relativity by

Dirac. In quantum chemistry, eigenvalues 'explain' the spectral lines that characterize chemical elements. In nuclear magnetic resonance, they reveal the molecular composition of a sample. In cosmology, gravitational eigen-waves derive from linearizing the general theory of relativity. In mechanical engineering, wave equations are abundant, with applications in acoustics, vibrational and modal analysis, etc. In data science, eigenvalues and -vectors appear in principal components and canonical correlation analysis, in graph spectral analysis, in spectral kernel methods, etc. In system theory, they are fundamental in characterizing stability and frequency content, observability and controllability and the very essence of control system design can be reduced to optimal eigenvalue placement.

Realization theory is about the equivalence between different mathematical representations of a dynamical system: from model-compliant data (i.e. data that belong to the behaviour of the system: they are compatible with the presumed model class), over input-output models, towards state space representations, etc. We will discuss a new framework of shift-invariant subspaces (single or multi-shift, forward and/or backward shift-invariant, causal and anti-causal models in one or several dimensions). These subspaces are characterized by the spectra of algebraic (generalized) eigenvalue problems, or multi-spectra of multi-parameter eigenvalue problems.

This framework provides solutions to a surprisingly wide variety of applications: linear and bilinear system identification from impulse trains, power spectrum and cepstrum realization, direction-of-arrival, and shape-from-moment problems, computing the roots of sets of multivariate polynomials, finding the global minima of multivariate polynomial optimization problems from an eigenvalue problem, etc.

Recently, we discovered the optimal least squares solution to the one-dimensional misfit realization problem for linear time-invariant models, starting from data that are not model-compliant. Such a 'noisy' realization problem can be solved exactly from a multi-dimensional realization problem via a multi-parameter eigenvalue problem. This basically solves the problem on how to least-squares approximate a Hankel matrix by a rank deficient one, that is also Hankel.

Non-Euclidean Geometry in System Theory and Identification

Prof. József Bókor, *SZTAKI Institute for Computer Science and Control, Budapest, Hungary*

Geometry is one of the richest areas for mathematical exploration. The visual aspects of the subject make exploration and experimentation natural and intuitive. At the same time, the abstractions developed to explain geometric patterns and connections make the approach extremely powerful and applicable to a wide variety of situations. Euclidean geometry includes a rich variety of concepts such as point, line, incidence, parallel lines, angle, distance between points, congruence of segments, and congruence of angles. Already from the beginning the fifth postulate was recognized as less obvious than the others. During more than two thousand years of fascinating mathematical history geometers were trying to either prove it from the other axioms or replace it by something more obvious. In the nineteenth century development of the Bolyai-Lobachevsky geometry, as the first instance of non-Euclidean geometries, had a great impact on the evolution of mathematical thinking. Non-Euclidean geometry has turned out to be more than just a logical curiosity, and many of its basic features continue to play important roles in several branches of mathematics and its applications.

The invention of Cartesian coordinates revolutionized mathematics by providing the first systematic link between Euclidean geometry and algebra, and provided enlightening geometric interpretations for many other branches of mathematics.

The main concern of this work is to highlight the deep relation that exists between the seemingly different fields of geometry, algebra and control theory. Felix Klein, in the late 1800s, proposed group theory as a tool for formulating and understanding geometrical constructions. The Kleinian view makes the link between geometry and group theory; Descartes provides the dictionary between the geometrical entities and the algebraic ones while through different representations and homomorphism the abstract group theoretical facts will obtain an algebraic (linear algebraic) formulation that open the way to engineering applications.

Concerning system modeling, the hyperbolic-distance defined by certain finite Blaschke-products plays a central role in modeling techniques that uses nonstandard system representations such as generalized orthogonal basis functions (GOBF). This was initiated by a Delft – research group represented by Paul van den Hof, Peter Heuberger and Okko Bosgra.

Related to the GOBF modeling and identification framework, an effective basis selection (pole selection) algorithm was developed based on hyperbolic-geometric results.

Concerning the time-domain development of robust control a possible model is the projective matrix space endowed with a hyperbolic metric. This framework allows us to relate the indefinite space approach (Grassmannian view, Krein-space approach) to the hyperbolic view. The central object is the (operator) matrix Möbius transformation and its domain. The properties of this transformation, i.e., the geometry, reveals the structure of robust control problems.

As a starting point of Euclidean and non-Euclidean worlds the most fundamental geometries are the projective and affine ones. Feedback stability is related to such geometries. Following the Kleinian project we identify the proper mathematical objects and the groups associated to these objects that are related to the concept of stability and stabilizing controllers. While traditional geometric control theory is centered on a local view based on differential geometry, a global view is centered on an input-output framework, based on a Kleinian approach to the geometry. Transformation groups play fundamental roles, since they leave a given global property, e.g., stability invariant. We put an emphasize on this concept of the geometry and its direct applicability to control problems. The method also provides tools for controller manipulations that preserves the property at hand, called controller blending.

Learning from data - model quality revisited

Prof. Raymond de Callafon, *University of California at San Diego, USA*

As terms such as learning, inference, correlation, optimization, modeling and inductive reasoning become commonplace in the emerging field of data science, it is worthwhile to reflect on the purpose of collecting and analyzing data. Data analysis can be characterized by reduction of (a large number N of) data points to a finite set of (a much smaller number $n < N$ of) systematic relations, often dubbed as a model. For this modeling process to be successful, fundamental concepts in data collection and modeling apply: the data must be informative, and the resulting model must be a trade-off between complexity, accuracy and sensitivity to noise variance.

Being fortunate to be exposed early on to these fundamental concepts in a course on "System Identification" taught by Prof. Van den Hof at Delft University of Technology, has sparked and continues to fire my interests in research and education in the subjects of learning, estimation and identification. I believe these subjects are essential in any science or engineering education to ensure data is analyzed properly. Inspired by the teaching of Prof. Van den Hof and my modest experience, this talk will briefly review common assumptions on data informativity and noise properties that influence model quality. It is shown that model quality assessment should depend on the intended use of the model, whereas model quality can be influenced by both experiment design and the above-mentioned trade-off. Examples obtained from electric power networks and wildfire progression are used to illustrate the fundamental concepts.

(My) user choices in system identification

em. Prof. Johan Schoukens, *Vrije Universiteit Brussel, Belgium*

Data driven modeling of dynamic systems, called system identification in the control community, is a complex process that is directed by several user choices throughout all the steps of the process: experiment design, model structure selection, choice of the estimation method, and model validation.
In this presentation, we will focus on a number of these choices and discuss their impact on the identified model:

Experiment design:
- Band-Limited or Zero-Order-Hold Setup
- Periodic excitations?

Model structure:
- Parametric or non-parametric plant and noise models
- Linear or nonlinear models

The estimation method: selection of a cost function
- Driven by the disturbing noise properties: reduce the variance. Driven by user choices: tune the structural model errors.
- Add regularization: balance bias versus variance.

The identification problem can be formulated either in the time- or in the frequency domain. Although both formulations are fully equivalent, it turns out that, from practical point of view, it can be advantageous to address some of the sub-steps of the identification process in one of both domains.

Beyond least squares

Prof. Marco Campi, *University of Brescia, Italy*

Least Squares is a mainstream approach in system identification, offering "centered" models suitable for diverse design problems. In many scientific endeavors, however, one rather aims at obtaining "coverage" models: the model defines a region in the domain of behaviors that covers cases with a high overall probability of occurrence. This paradigm is applied in fields like social demography and for generating interval predictions in medical and financial applications. Quite interestingly, recent findings have yielded profound insights capable of accurately assessing the quality of coverage models. This is crucial for trust-building, as well as for the selection of suitable values to assign to their hyper-parameters. Comparing Least Squares and coverage models raises truly fascinating issues of investigation.

12:00 **Lunch break**

13:00 **Afternoon session**

Full Bayesian identification of linear dynamic systems using stable kernels

Prof. Lennart Ljung, *Linköping University, Sweden*

It is known that identification of linear systems using regularized high order ARX-models typically outperforms traditional Maximum Likelihood (ML) estimation of models with selected model orders. Then the regularization is using an “Empirical Bayes” technique. This means that the hyperparameters (decay and correlation of the impulse responses) are estimated from data using ML.

In this contribution we take the Bayesian approach one step further: The hyperparameters are themselves seen as random variables, and their posterior distributions are used when computing the (posterior) model. An MCMC scheme is developed for this identification method. Numerical experiments show that this “Full Bayes” frequently outperforms the state-of-the-art results on typical benchmark problems.

The method is a joint work with Gianluigi Pillonetto and was recently published:
G. Pillonetto and L. Ljung: Full Bayesian identification of linear dynamic systems using stable kernels. Proc National Academy of Sciences, PNAS, Vol 120 (18), 2023, e2218197120

Orthonormal basis functions models: beyond the LTI case

Prof. Roland Tóth, *TU Eindhoven and SZTAKI Institute for Computer Science and Control, Budapest, Hungary*

Prof.dr.ir. Paul Van den Hof made pioneering contributions in establishing the system theory and the identification methods for the use of Orthonormal Basis Functions (OBFs) in data-driven modelling of Linear Time Invariant (LTI) systems. However, was this established powerful framework meant to be confined for LTI systems? Fated to be serving the machinery of system identification only? To answer these questions, we will explore how OBFs have contributed to the identification and Bayesian learning of Linear Parameter-Varying (LPV) and nonlinear systems. Why the optimal pole selection problem was a serious challenge for these beyond LTI model structures and what kind of solutions have been developed. Finally, we give a glimpse into how OBF-based model structures contributed to the development of adaptive predictive control methods.

I4C: First there was variance, then bias, what now?
Prof. Håkan Hjalmarsson, *KTH Stockholm, Sweden*

Starting a PhD in system identification in 1988 as I did was perfect timing. Major advances had recently been made in robust control and the time was ripe to link model uncertainty from identified models with this powerful framework.
In identification, the variance error had up to now been considered the major error source but robust control cast the spotlight on the high complexity of real-world systems and that the robustness feedback provides should allow the use of models of restricted complexity. With this as backdrop, identification for control quickly became vibrant with activities. Much work centered around how to obtain experimental conditions such that the bias error was optimally distributed with respect to the resulting closed loop performance. A very hard problem. One of the benefits of such problems is that they promote highly innovative ideas and the flurry of ideas that were spawned out of this challenge has continued to ripple through generations of PhD students, resulting in yet new ideas, which today resonate together making the area more vital than ever with a strong focus on predictive control.

In this talk, I will take a step back and consider the problem of data-driven control from a statistical decision theory point of view, discussing issues such as i) fundamental performance limitations. ii) model-based or direct data-driven control, does it matter? iii) leveraging the bias-variance trade-off, iv) the role of experiment design. Hopefully, my observations can add to the ripple.

Identification for control
Prof. Tom Oomen, *TU Eindhoven and TU Delft*

The accuracy of identified models hinges on its purpose. The aim in this presentation is identify models tailored to the purpose of control design. The main methodology is to connect coprime factorization-based identification, control-relevant identification, and robust control design. This integrates developments in identification for control over the past few decades to a full design framework from data to control performance. Finally, recent developments are outlined, enabling an interpretation of the identified models.

The Evolving Landscape of Data-driven modeling in Dynamic Networks: Retrospect and Prospect
Dr. Karthik Ramaswamy, *ASML Veldhoven, The Netherlands*

This talk navigates through the dynamic history and promising future of data-driven modeling in dynamic networks. The retrospective journey unfolds the foundational principles and key advancements in the past decade, with a spotlight on the pioneering work of prof. Paul. As we delve into the present landscape, we explore the integration of sophisticated algorithms and cutting-edge tools, including machine learning, in refining network identification methodologies. The prospect section ventures into possible future developments, envisioning the evolving role of dynamic network identification in addressing complex challenges.

15:05	**Break**
16:00	**Valedictory lecture by Prof. Paul Van den Hof in the Blauwe Zaal, Auditorium TU/e**
17:00	**Reception**
18:30	**End**

More information on the symposium contributions is available at:
www.tue.nl/lectureVandenHof

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Attendance is free of charge, but registration is required.
You may register via: **https://forms.office.com/e/f6CfqzsAv1**
Registration closes **March 15, 2024**.
For more information please contact: **secretariaat.cs@tue.nl**