Data-based Methods for Interconnected Systems: Theory and Algorithms

Anne Koch [*] **Maria Prandini** [**]

[*] *Institute for Systems Theory and Automatic Control, Stuttgart University, Stuttgart, Germany (e-mail: anne.koch@ist.uni-stuttgart.de)*
[**] *Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milano, Italy (e-mail: maria.prandini@polimi.it)*

Abstract: We propose a one-day workshop to highlight recent developments in data-based analysis and design that have been motivated by emerging applications involving multiple interconnected systems. This poses new challenges to traditional data-based approaches and calls for further theoretical and algorithmic developments.
The goal of the workshop is to provide a wide coverage of the field, including modeling, analysis, control and optimization, while offering new vistas. To this purpose, we bring together outstanding researchers from leading institutions worldwide. Target audience comprises graduate level control engineers, as well as researchers with a strong interest in data-based approaches.

Keywords: Data-based methods; Identification of interconnected systems; Distributed control and optimization; Learning in multi-agent systems; Security in distributed systems.

1. WORKSHOP STRUCTURE

The workshop brings together outstanding researchers in the field of data-based analysis and design, from leading universities and institutions in Europe, Japan, and the United States, and promises a balanced and broad introduction to the topic. In the sequel we provide the list of talks with abstracts, and brief biographies of the speakers, in alphabetic order based on their surname.

1.1 Presentations: titles and abstracts

Learning of interconnected dynamical systems – Håkan Hjalmarsson, KTH, Stockholm, Sweden

Key issues in data-driven learning of interconnected dynamical systems include topology detection, identifiability analysis, and identification of the dynamics, both of entire interconnected systems as well as individual modules. We present an overview of these topics together with state-of-the art results. Central to our exposition are statistical considerations. Both non-parametric (kernel based) and parametric methods are discussed. The thrust is on linear time-invariant models but we also provide excursions into the more diverse non-linear landscape.

Dynamic Networks: representation and identification – Alessandro Chiuso, University of Padova, Padova, Italy

In this talk we shall discuss representation and identification of interconnected dynamic systems. First several notions of dynamic networks shall be introduced and their relation discussed. In the context of internally stable interconnections, we shall focus on a canonical representation that is identifiable without additional structural assumptions. Algorithmic and statistical issues related to the network identification problem will then be discussed in the context of sparse estimation. Extensions and applications will conclude the presentation.

A distributed data-based approach to multi-agent decision-making – Alessandro Falsone, Politecnico di Milano, Milano, Italy

We consider multi-agent decision-making problems that can be formulated as optimization programs where each agent introduces its own constraints on the optimization vector, and the constraints of all agents depend on a common source of uncertainty. We suppose that uncertainty is known locally to each agent through a private set of data, and that each agent enforces its data-based constraints to the solution of the multi-agent optimization problem. Our goal is to assess the feasibility properties of the corresponding multi-agent data-based solution and provide distributed resolution algorithms that can cope with heterogeneity of the agents, privacy of their local data, and combinatorial complexity when discrete decision variables are involved. Possible application to energy systems are presented to showcase our results.

Resilience and privacy issues in distributed algorithms – Hideaki Ishii, Tokyo Institute of Technology, Tokyo, Japan

The wide use of networking has enabled various cyber-physical devices to be connected for carrying out collaborative computation for control and estimation purposes. At the same time, however, risks of cyber attacks have drastically increased, which can result not only in having important and private data to be stolen, but also devices to be remotely manipulated in a stealthy manner by adversaries. In this talk, we present how to protect distributed algorithms from malicious attackers by raising the security levels in terms of their resilience and privacy preservation. Particular attention will be given to the multi-agent consensus problem. We will see how false data injection type attacks as well as eavesdropping type attacks can harm the system. Then, we provide several solutions for addressing such issues. We will further discuss that cyber security of distributed algorithms is in fact an interesting area for interdisciplinary research, connecting systems control with computer science.

Event-triggered Learning – Sebastian Trimpe, RWTH Aachen University, Aachen, Germany

The ability to learn is an essential aspect of autonomous systems facing uncertain and changing environments. However, the process of learning a new model or behavior often does not come for free, but involves a certain cost. For example, gathering informative data can be challenging due to physical limitations, or updating models can require substantial computation. Moreover, learning for autonomous agents often requires exploring new behavior and thus typically means deviating from nominal or desired behavior. Hence, the question of "when to learn?" is essential for the efficient and intelligent operation of autonomous systems. We have recently proposed the concept of event-triggered learning (ETL) for making principled decisions on when to learn new dynamics models. Building on the core idea of learning only when necessary, we have developed concrete triggers and theory for different domains. In the context of networked and interconnected systems, ETL leads to superior communication savings over standard event-triggered control. For linear quadratic control, ETL automatically detects inaccurate models and yields improved control performance under changing dynamics. In this talk, we present the concept, theoretical results, and experimental applications of ETL.

On the sample complexity of distributed linear optimal controllers – Nikolai Matni, University of Pennsylvania, Philadelphia, US

We propose a robust control based approach to designing distributed controllers for unknown-but-sparse linear and time invariant systems. By leveraging modern techniques in sparse system identification and distributed robust controller synthesis, we show that near-optimal distributed controllers can be learned with sub-linear sample complexity and computed with near-linear computational complexity, both measured with respect to the dimension of the full system. In particular, we provide end-to-end Probably Approximately Correct (PAC) bounds on the stability and performance of the designed distributed controller, and prove that for sparse systems, the number of samples needed to guarantee robust and near optimal performance can be much smaller than the dimension of the full system. Although the proposed optimization problem is quasi-convex, we show that it can be solved to global optimality by iteratively solving a series of small quadratic programs. We end with a demonstration of our results on a large-scale power-system inspired example.

Uncovering novel systems analysis and design principles through particle-based considerations – Shen Zeng, Washington University, St. Louis, US

In the past decades, modeling and control were mostly concerned with exclusively one dynamical system with relatively mild complexity, which allowed for a highly successful systems theoretic treatment by purely analytical methods. However, recent years have witnessed a significant shift towards far more complex and large-scale dynamical systems in virtually all of the applied sciences, in which a traditional analytical approach is infeasible. This trend highlights the need for the exploration and development of novel systems analysis and design principles that are specifically applicable to complex and large-scale dynamical systems. In this talk, I will first introduce the very fruitful approach associated with viewing a complex dynamical system in a more global fashion, i.e. in terms of its macroscopic behavior. After providing a rapid review of the corresponding theory of transport operators (which are the adjoints of the Koopman operators), I will describe recent developments of employing sample-based approaches to efficiently elucidate and compute important dynamical features in complex systems, such as invariant sets and measures, isochrons, as well as more systems theoretic features, such as global observability measures for nonlinear systems. In contrast to parametric approaches employing function libraries for describing the spatio-temporal patters to be computed, sample-based, or, nonparametric, approaches are often more flexible and computationally more efficient.

Data-enabled predictive control (DeePC) – Florian Dörfler, ETH Zürich, Switzerland

We consider the problem of optimal and constrained control for unknown systems. A novel data-enabled predictive control (DeePC) algorithm is presented that computes optimal and safe control policies using real-time feedback driving the unknown system along a desired trajectory while satisfying system constraints. Using a finite number of data samples from the unknown system, our proposed algorithm uses a behavioral systems theory approach to learn a non-parametric system model used to predict future trajectories. We show that, in the case of deterministic linear time-invariant systems, the DeePC algorithm is equivalent to the widely adopted Model Predictive Control (MPC), but it generally outperforms subsequent system identification and model-based control. To cope with nonlinear and stochastic systems, we propose salient regularizations to the DeePC algorithm. Using techniques from distributionally robust stochastic optimization, we prove that these regularization indeed robustify DeePC against corrupted data. We illustrate our results with nonlinear and noisy simulations and experiments from aerial robotics, power electronics, and power systems.

1.2 Biographies of the speakers

Alessandro Chiuso is Professor with the Department of Information Engineering, University of Padova. He received the "Laurea" degree summa cum laude in Telecommunication Engineering from the University of Padova in July 1996 and the Ph.D. degree in System Engineering from the University of Bologna in 2000. He has been visiting research scholar with Washington University St. Louis (USA) and a Postdoctoral Fellow with KTH (Sweden). Dr. Chiuso is chair of the IFAC TC1.1, an Associate Editor of Automatica (since 2008), European Journal of Control (since 2011). He was an Associate Editor of IEEE Transactions on Automatic Control (2010-12), IEEE Transactions on Control Systems Technology (2013-17), the IEEE Conference Editorial Board (2004-09) and a member of the editorial board of IET Control Theory and Application (2007-12). He also serves or has served as member of several conference program committees and technical committees. His research interest are mainly in Machine Learning, Estimation, Identification Theory and Applications.

Florian Dörfler is an Associate Professor at the Automatic Control Laboratory at ETH Zürich. He received his Ph.D. degree in Mechanical Engineering from the University of California at Santa Barbara in 2013, and a Diplom degree in Engineering Cybernetics from the University of Stuttgart in 2008. From 2013 to 2014 he was an Assistant Professor at the University of California Los Angeles. His students were winners or finalists for Best Student Paper awards at the 2019 and 2013 European Control Conference, the 2016 American Control Conference, and the 2017 PES PowerTech Conference. His articles received the 2010 ACC Student Best Paper Award, the 2011 O. Hugo Schuck Best Paper Award, the 2012-2014 Automatica Best Paper Award, and the 2016 IEEE Circuits and Systems Guillemin-Cauer Best Paper Award. He is a recipient of the 2009 Regents Special International Fellowship, the 2011 Peter J. Frenkel Foundation Fellowship, and the 2015 UCSB ME Best PhD award.

Alessandro Falsone received his Master degree in Automation and Control Engineering in 2013, and his PhD degree in Information Engineering, in 2018, both with laude and from Politecnico di Milano. During his PhD studies he spent three months as a visiting researcher at the University of Oxford. Since 2018, he is a junior assistant professor at the Dipartimento di Elettronica, Informazione e Bioingegneria at Politecnico di Milano. His current research interests include distributed optimization and control, optimal control of stochastic hybrid systems, randomized algorithms, and nonlinear model identification. In 2018 he was the recipient of the Dimitris N. Chorafas Prize for his PhD thesis. In 2019 he received the IEEE CSS Italy Chapter Best Young Author Journal Paper Award.

Håkan Hjalmarsson was born in 1962. He received the M.S. degree in Electrical Engineering in 1988, and the Licentiate degree and the Ph.D. degree in Automatic Control in 1990 and 1993, respectively, all from Linköping University, Sweden. He has held visiting research positions at California Institute of Technology, Louvain University and at the University of Newcastle, Australia. He has served as an Associate Editor for Automatica (1996-2001), and IEEE Transactions on Automatic Control (2005-2007) and been Guest Editor for European Journal of Control and Control Engineering Practice. He is Professor at the Division of Decision and Control Systems, School of Electrical Engineering and Computer Science, KTH, Stockholm, Sweden and also affiliated with the Competence Centre for Advanced BioProduction by Continuous Processing, AdBIOPRO. He is an IEEE Fellow and past Chair of the IFAC Coordinating Committee CC1 Systems and Signals. In 2001 he received the KTH award for outstanding contribution to undergraduate education. He was General Chair for the IFAC Symposium on System Identification in 2018. His research interests include system identification, learning of dynamical systems for control, process modeling and control and also estimation in communication networks.

Hideaki Ishii received the M.Eng. degree in applied systems science from Kyoto University in 1998, and the Ph.D. degree in electrical and computer engineering from the University of Toronto in 2002. He was a Postdoctoral Research Associate with the Coordinated Science Laboratory at the University of Illinois at Urbana-Champaign from 2001 to 2004, and a Research Associate with the Department of Information Physics and Computing, The University of Tokyo from 2004 to 2007. Currently, he is an Associate Professor in the Department of Computer Science, Tokyo Institute of Technology. He was a Humboldt Research Fellow at the University of Stuttgart in 2014-2015. His research interests are in networked control systems, multi-agent systems, hybrid systems, cyber security of power systems, and probabilistic algorithms. Dr. Ishii has served as an Associate Editor for the IEEE Control Systems Letters, and Mathematics of Control, Signals, and Systems, and previously for Automatica, the IEEE Transactions on Automatic Control, and the IEEE Transactions on Control of Network Systems. He is the Chair of the IFAC Coordinating Committee on Systems and Signals and was the Chair of the IFAC Technical Committee on Networked Systems from 2011 to 2017. He received the IEEE Control Systems Magazine Outstanding Paper Award in 2015.

Nikolai Matni is an Assistant Professor in the Department of Electrical and Systems Engineering, University of Pennsylvania. Prior to joining Penn, Nikolai was a postdoctoral scholar in EECS at UC Berkeley. He has also held a position as a postdoctoral scholar in the Computing and Mathematical Sciences at Caltech. He received his Ph.D. in Control and Dynamical Systems from Caltech in June 2016. He also holds B.A.Sc. and M.A.Sc. in Electrical Engineering from the University of British Columbia, Vancouver, Canada. His research interests broadly encompass the use of learning, optimization, and control in the design and analysis of safety-critical and data-driven cyber-physical systems. He was awarded the IEEE CDC 2013 Best Student Paper Award (first ever sole author winner) and the IEEE ACC 2017 Best Student Paper Award (as co-advisor).

Sebastian Trimpe is a Full Professor at RWTH Aachen University, where he leads the Institute for Data Science in Mechanical Engineering (DSME) since May 2020. Research as DSME focusses on fundamental questions at the intersection of control, machine learning, networks, and robotics. Before moving to RWTH, Sebastian was a Max Planck and Cyber Valley Research Group Leader at the Max Planck Institute (MPI) for Intelligent Systems in Stuttgart, Germany. Sebastian obtained his Ph.D. degree in 2013 from ETH Zurich with Raffaello D'Andrea at the Institute for Dynamic Systems and Control. Before, he received a B.Sc. degree in General Engineering Science in 2005, a M.Sc. degree (Dipl.-Ing.) in Electrical Engineering in 2007, and an MBA degree in Technology Management in 2007, all from Hamburg University of Technology. In 2007, he was a research scholar at the University of California at Berkeley. Sebastian is recipient of the triennial IFAC World Congress Interactive Paper Prize (2011), the Klaus Tschira Award for achievements in public understanding of science (2014), the Best Demo Award of the International Conference on Information Processing in Sensor Networks (2019), and the Best Paper Award of the International Conference on Cyber-Physical Systems (2019).

Shen Zeng is an Assistant Professor in the Electrical and Systems Engineering Department at Washington University in St. Louis. He studied Engineering Cybernetics, Mechatronics, and Mathematics at the University of Stuttgart, where he also received a Ph.D. degree in 2016. His research interests are in systems and control theory with a focus on analytic, algebraic, and geometric methods, and more recently, computational, methods.

1.3 Biographies of the organizers

Anne Koch received the M.Sc. in Engineering Science and Mechanics from the Georgia Institute of Technology, Atlanta, USA, in 2014, and the M.Sc. in Engineering Cybernetics from the University of Stuttgart, Germany, in 2016. In 2016, she joint the Institute for Systems Theory and Automatic Control at the University of Stuttgart as a research and teaching assistant pursuing the Ph.D. degree within the International Max Planck Research School for Intelligent Systems. Her research interests include data-based systems analysis and controller design.

Maria Prandini received her Ph.D. degree in Information Technology in 1998. She was a postdoctoral researcher at UC Berkeley (1998-2000). She also held visiting positions at Delft University of Technology (1998), Cambridge University (2000), UC Berkeley (2005), and ETH Zurich (2006). In 2002, she became an assistant professor of automatic control at Politecnico di Milano, where she is currently a full professor. She was editor for the IEEE CSS Electronic Publications (2013-15), elected member of the IEEE CSS Board of Governors (2015-17), elected member of the IEEE CSS nominating committee (2018) and IEEE CSS Vice-President for Conference Activities (2016-17). She is program chair of the IEEE Conference on Decision and Control (CDC) 2021, vice-program chair of the IEEE CDC 2020, and an associate editor of the IEEE Transactions on Network Systems. She is member of the IFAC Policy Committee for the triennium 2017-20. In 2018, she received the IEEE CSS Distinguished Member Award. Her research interests include stochastic hybrid systems, randomized algorithms, distributed and data-based optimization, multi-agent systems, and the application of control theory to transportation and energy systems.