2nd Brig Workshop on

# Dissipativity in Systems and Control

**May 21–24, 2024 in Brig, Switzerland**

# Program & Book of Abstracts




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# 1 General

## 1.1 Scope

The workshop will address recent progress on dissipativity in systems and control, including
- the exploitation of dissipative and port-Hamiltonian system structures in control,
- simulation and optimization of dissipative systems,
- energy-based modeling concepts,
- structure-preserving model reduction methods, and
- data-driven control methods.

## 1.2 Organizers

The scientific organizing committee consists of
- Timm Faulwasser (TU Hamburg, Germany),
- Benjamin Unger (U Stuttgart, Germany),
- Matthias Voigt (UniDistance Suisse, Brig, Switzerland).

Further local support is provided by Milène Fauquex, Fabienne Troger, and Manuela Weber.

## 1.3 Acknowledgement

The organizers wish to thank the Swiss National Science Foundation (SNF) as well as UniDistance Suisse who generously support this event.

# 2 Organization

## 2.1 Location

The workshop will take place in the assembly hall of the new campus building of UniDistance Suisse and Fernfachhochschule Schweiz (Schinerstrasse 18, 3900 Brig, Switzerland).

## 2.2 Internet Access

There is a free wifi access point in the campus. You can either use `Eduroam` or connect to `FernUni-Gast`, which is available after you have registered with your mobile phone number.

## 2.3 Lunches

Lunches are to be self-organized. There are several good nearby restaurants that often also offer a special lunch menu for a reduced price. Many restaurants are located in the town center of Brig which is just a 10 minutes walk away from the campus building. Here are a few suggestions:
- **Walliserstuba**, Bahnhofstrasse 9, 3900 Brig (550m from the campus),
- **Yuan–China Restaurant**, Rhonesandstrasse 4, 3900 Brig (500m from the campus),
- **Channa**, Furkastrasse 5, 3900 Brig (500m from the campus),

## 2.4 Hike

We will hike the beautiful Swiss Alps and plan with the following schedule:

- **13:15** Meeting in front of the Brig train station
- **13:34** Take the train to Hohtenn
- **14:00** Start of the hike along the "Lötschberger Südrampe" (9.4km) to Ausserberg.
- **18:20/19:20** Arrival in Brig via train.

Please make sure to wear appropriate clothes and use sun cream. Also, it is advisable to bring some water, food, and cash[1] with you.

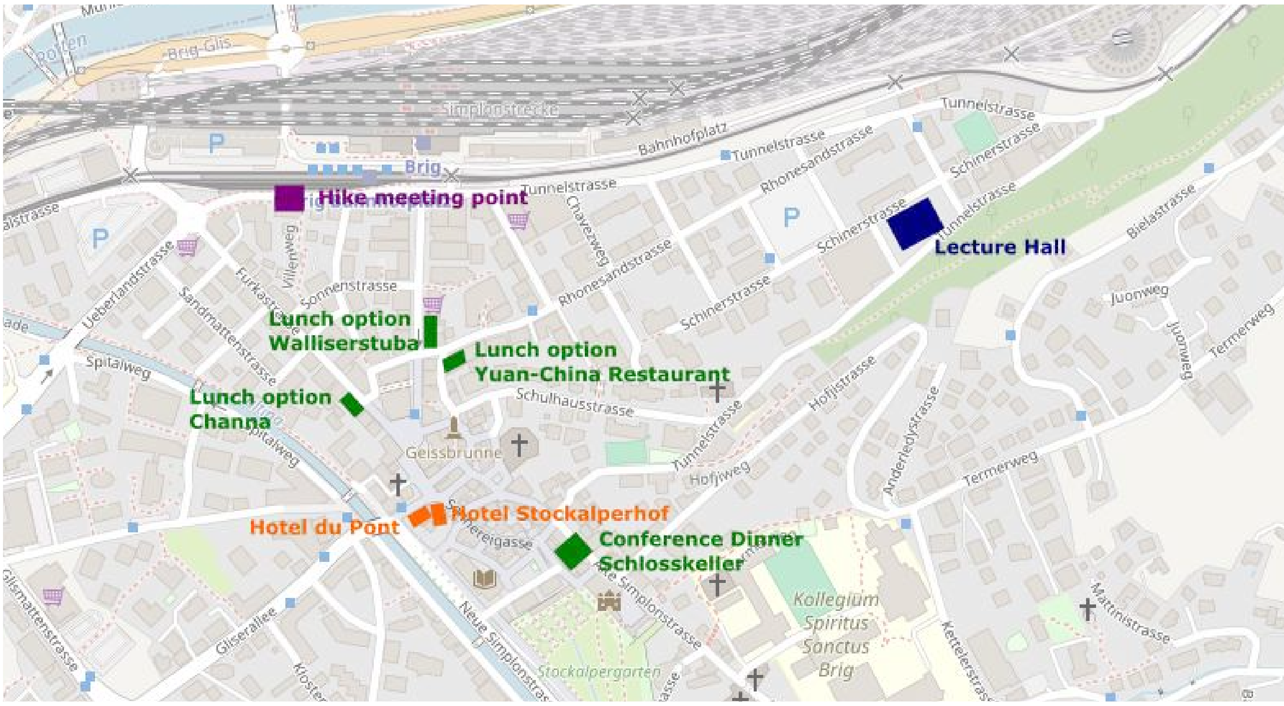
## 2.5 Conference Dinner

The conference dinner will take place on Thursday, May 23, starting at 7pm at Schlosskeller Brig (Alte Simplonstrasse 26, 3900 Brig). The following menu has been prepared for us:

Mixed Schlosskeller salad with balsamico dressing
***
Piccata milanese with spaghetti on tomato-basil sauce with zucchini (chicken)
or
Creamy saffron risotto with aragula, confit mushrooms, and parmesan chips (vegetarian)
***
Sorbet with fresh seasonal fruits

The dinner will include a limited amount water and wine. Please expect costs of about 60–65 CHF (depending on how much you consume). **Please pay the dinner by yourself when leaving the restaurant.**

## 2.6 Map

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[1]Paying with card might not be possible in all restaurants.

# 3 Daily Program

## 3.1 Tuesday, May 21, 2024

| | |
|---|---|
| 08:55 | *Opening (Matthias Voigt)* |
| 09:00 | **Björn Liljegren-Sailer**<br>Structure-preserving discretization and model reduction in the pH framework |
| 10:00 | *Coffee Break* |
| 10:30 | **Riccardo Morandin**<br>Modeling and discretization of general port-Hamiltonian descriptor systems |
| 11:00 | **Michael Günther**<br>Operator splitting schemes for port-Hamiltonian differential-algebraic equations |
| 11:30 | **Attila Karsai**<br>Structure preserving time discretization of port-Hamiltonian systems |
| 12:00 | *Lunch Break* |
| 14:00 | **Kanat Camlibel**<br>System identification and dissipativity inference from input-output data |
| 15:00 | **Jens Püttschneider**<br>Dissipativity Properties in Neural Network Training |
| 15:30 | **Luca Furieri**<br>Learning to optimize with convergence guarantees |
| 16:00 | *Coffee Break* |
| 16:30 | **Leonardo Massai**<br>Unconstrained learning of networked nonlinear systems via free parametrization of stable interconnected operators |
| 17:00 | **Muhammad Zakwan**<br>Neural Distributed Controllers with Port-Hamiltonian Structures |
| 17:30 | **Danilo Saccani**<br>Learning Stabilizing Distributed Optimal Control for Nonlinear Systems through Neural Closed-Loop Maps |
| 18:00 | Apéro |

## 3.2 Wednesday, May 22, 2024

| | |
|---|---|
| 09:00 | **Bernhard Maschke**<br>Various representations of Boundary Port Hamiltonian Systems |
| 10:00 | *Coffee Break* |
| 10:30 | **Till Preuster**<br>Jet space extensions of infinite-dimensional Hamiltonian systems |
| 11:00 | **Illia Karabash**<br>Homogenization and optimization of eigenvalues of dissipative Maxwell systems |
| 11:30 | *Lunch* |
| 13:15 | Sart of the *Hike* (Meeting point in front of the train station) |

## 3.3 Thursday, May 23, 2024

| | |
|---|---|
| 09:00 | **Claudia Totzeck**<br>On the port-Hamiltonian structure of interacting particle systems |
| 10:00 | *Coffee Break* |
| 10:30 | **Tatjana Stykel**<br>Passivity-preserving model reduction of quasilinear magneto-quasistatic feld problems |
| 11:10 | **Benjamin Unger**<br>Passivity-preserving model reduction for passive descriptor systems |
| 11:40 | **Michał Wojtylak**<br>Singular operator pencils |
| 12:10 | *Lunch Break* |
| 14:00 | **Matthias A. Müller**<br>Incremental dissipativity and its application in optimization-based state estimation |
| 15:00 | **Max Sibeijn**<br>Strict Dissipativity for Economic Model Predictive Control of District Heating Networks: Challenges and Solutions |
| 15:30 | **Timm Faulwasser**<br>Causality Structures in Stochastic Optimal Control |
| 16:00 | *Coffee Break* |
| 16:30 | **Jonas Schießl**<br>Dissipativity and Turnpike in Stochastic Optimal Control |
| 17:00 | **Morteza Nazari Monfared**<br>Passivity-based Control of DC-DC Boost Converters |
| 17:30 | **Mohammad Itani**<br>Predictive Path-Following based on Manifold Turnpikes and Dissipativity |
| 19:00 | *Conference Dinner* at Schlosskeller Brig |

## 3.4 Friday, May 24, 2024

| | |
|---|---|
| 09:30 | **Hannes Gernandt**<br>Port-Hamiltonian perspectives in modeling and control of multi-energy networks |
| 10:30 | *Coffee Break* |
| 11:00 | **Markus Lohmayer**<br>Recent progress on the EPHS modeling language: Multibody systems and discrete-time semantics |
| 11:40 | **Dorothea Hinsen**<br>Relationships between dissipativity concepts for linear time-varying port-Hamiltonian systems |
| 12:10 | **Vaibhav Kumar Singh**<br>Finite-time output consensus for a network of nonlinear agents: Krasovskii and shifted passivity |
| 12:40 | *Closing (Matthias Voigt)* |

# 4 Abstracts

## Structure-preserving discretization and model reduction in the pH framework

Björn Liljegren-Sailer (RICAM and MathConsult, Linz, Austria)

The port-Hamiltonian framework can be used for the structured modeling of dynamical systems [5]. Its modularized nature and energy-based interpretation have also proven to be advantageous for the design of structured approximations, as it provides a systematic approach to encoding geometric structures in an algebraic way. By preserving or mimicking relevant geometric structures such as, e.g., conservation laws or symplecticities, unphysical solution behavior and numerical instabilities can be avoided in many cases.

In this talk, different aspects of the structure-preserving approximation in the port-Hamiltonian framework are addressed. In particular, we touch upon the higher complexity in time-discretization as compared to the strictly Hamiltonian case [2, 3]. Moreover, we discuss snapshot-based model order- and complexity-reduction under compatibility conditions, which is a natural approach to port-Hamiltonian model reduction. For certain problem classes, efficient implementations have been derived [4, 6], while for other problem classes the realization of compatible reduced models remains numerically challenging [1].

[1] C. Engwer, M. Ohlberger, and L. Renelt. Model order reduction of an ultraweak and optimally stable variational formulation for parametrized reactive transport problems. *arXiv:2310.19674*, 2023.

[2] A. Frommer, M. Günther, B. Liljegren-Sailer, and N. Marheineke. Operator splitting for port-Hamiltonian systems. arXiv:2201.06631, 2023.

[3] M. Kolmbauer, G. Offner, R. U. Pfau, and B. Pöchtrager. Multirate DAE-simulation and its application in system simulation software for the development of electric vehicles. *J. Math. Ind.*, 12(1):11, 2022.

[4] B. Liljegren-Sailer and N. Marheineke. On snapshot-based model reduction under compatibility conditions for a nonlinear flow problem on networks. 92(62), 2022.

[5] B. M. Maschke and A. J. van der Schaft. Port-controlled Hamiltonian systems: modelling origins and systemtheoretic properties. Selected Papers from the 2nd IFAC Symposium, Bordeaux, France 1992, 359–365, 1993.

[6] N. Stahl, B. Liljegren-Sailer, and N. Marheineke. Certified reduced basis method for the damped wave equations on networks. *IFAC-PapersOnLine*, 55(20):289–294, 2022.

## Modeling and discretization of general port-Hamiltonian descriptor systems

Riccardo Morandin (Technische Universität Berlin, Germany)

Port-Hamiltonian descriptor systems combine port-Hamiltonian (pH) systems [1] with differential-algebraic equations (DAE) [2] using the language of control theory. We present a general definition of pHDAEs, that deals with finite-dimensional, infinite-dimensional and hybrid systems in the same way. In fact, we consider systems of the form

$$\begin{aligned} E(x)\dot{x} &= A(x)z(x) + B(x)u(x), \\ y &= C(x)z(x) + D(x)u(x), \end{aligned} \tag{4.1}$$

where $x \in \mathcal{X}$ is the state, $\dot{x} \in \mathcal{W}$ is the velocity, $u \in \mathcal{U}$ and $y \in \mathcal{Y}$ are the input and output variables, respectively, $z : \mathcal{X} \to \mathcal{F}$ is called the *co-state*, and the coefficients $E(x) : \mathcal{W} \to \mathcal{E}$, $A(x) : \mathcal{F} \to \mathcal{E}$,

$B(x) : \mathcal{U} \to \mathcal{E}$, $C(x) : \mathcal{F} \to \mathcal{Y}$, and $D(x) : \mathcal{U} \to \mathcal{Y}$ are state-dependent linear operators, where $\mathcal{X}, \mathcal{W}, \mathcal{U}, \mathcal{Y}, \mathcal{F}$, and $\mathcal{E}$ are appropriate vector spaces. The pairs of spaces $(\mathcal{F}, \mathcal{E})$, $(\mathcal{U}, \mathcal{Y})$ and $(\mathcal{W}, \mathcal{W}^\star)$ are equipped with appropriate real-valued nondegenerate bilinear forms, so that it makes sense to consider operators which are *transpose* to the coefficients. The system (4.1) is provided with a *Hamiltonian* $\mathcal{H} : \mathcal{X} \to \mathbb{R}$ that is differentiable in the sense that there is $\partial\mathcal{H} : \mathcal{X} \to \mathcal{W}^\star$ satisfying the chain rule $\frac{\mathrm{d}}{\mathrm{d}t}(\mathcal{H} \circ x) = (\partial\mathcal{H} \circ x)\dot{x}$ along all differentiable trajectories $x$. We call (4.1) *port-Hamiltonian* if

$$\begin{bmatrix} A(x) & B(x) \\ -C(x) & -D(x) \end{bmatrix} = L(x) - W(x)$$

with $L(x) = -L(x)^\top$ and $W(x) = W(x)^\top \geq 0$, and $E(x)^\top z(x) = \partial\mathcal{H}(x)$, for all $x \in \mathcal{X}$.

Many different systems, both finite- and infinite-dimensional, and with classical and weak solutions, fit into this framework. We make use of the flexible DAE structure, that allows e.g. to include boundary control explicitly in the equations in a structured way. This framework can also be extended to the case where $\mathcal{X}$ is more in general a topological space, and $\mathcal{W}, \mathcal{U}, \mathcal{Y}, \mathcal{F}, \mathcal{E}$ are (possibly infinite-dimensional) vector bundles on $\mathcal{X}$.

To discretize the system (4.1), we suggest a Galerkin projection paradigm, that obtains without fail a finite-dimensional pHDAE, preserving the structure. The main idea consists in interpreting the co-state $z$ as its own variable, and adding the condition $E(x)^\top z = \partial\mathcal{H}(x)$ to the equations, obtaining the *Dirac-dissipative representation*

$$\begin{bmatrix} \partial\mathcal{H}(x) \\ 0 \\ -y \end{bmatrix} + \begin{bmatrix} 0 & -E(x)^\top & 0 \\ E(x) & A(x) & B(x) \\ 0 & -C(x) & -D(x) \end{bmatrix} \begin{bmatrix} -\dot{x} \\ z \\ u \end{bmatrix} = 0. \tag{4.2}$$

It turns out that (4.2) is in general easier to discretize than (4.1), if one wants to preserve the pH structure. We investigate advantages and downsides of this method. Furthermore, this approach can be applied with minor modifications to achieve structure-preserving model order reduction, or even time discretization.

This work is based on my doctoral thesis [3].


[1] A. van der Schaft, and D. Jeltsema. Port-Hamiltonian Systems Theory: An Introductory Overview. *Found. Trends Syst. Control*, 1(2-3):173–378, 2014.

[2] P. Kunkel, and V. Mehrmann. Differential-Algebraic Equations. Analysis and Numerical Solution. *EMS Publishing House*, 2006.

[3] R. Morandin. Modeling and numerical treatment of port-Hamiltonian descriptor systems. *Dissertation*, Technische Universität Berlin, 2023.


## Operator splitting schemes for port-Hamiltonian differential-algebraic equations


Michael Günther (Bergische Universität Wuppertal, IMACM, Germany)
Andreas Bartel (Bergische Universität Wuppertal, IMACM, Germany)
Malak Diab (Bergische Universität Wuppertal, IMACM, Germany)
Andreas Frommer (Bergische Universität Wuppertal, IMACM, Germany)
Nicole Marheineke (Universität Trier, Fachbereich Mathematik, Germany)


The energy-based formulation of port-Hamiltonian differential algebraic systems (pH-DAEs) encodes physical properties directly into the equations. In the context of simulation, it is essential to employ numerical schemes that take into account the inherent structure and maintain explicit or hidden algebraic constraints without altering them. This paper focuses on operator-splitting techniques that preserve the structure in the port-Hamiltonian framework. The study explores two decomposition strategies: one considering the underlying coupled subsystem structure and the other addressing energy-associated properties such as conservation and dissipation.

We show that for coupled index-1 differential-algebraic equations (DAEs) with and without private index-2 variables, the splitting schemes on top of a dimension-reducing decomposition achieve the same convergence rate as in the case of ordinary differential equations.

Additionally, we discuss an energy-associated decomposition for index-1 pH-DAEs and introduce generalized Cayley transforms to uphold energy conservation. The effectiveness of both strategies is evaluated using port-Hamiltonian benchmark examples from electric circuits.

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## Structure preserving time discretization of port-Hamiltonian systems

Attila Karsai (Technische Universität Berlin, Germany)
Jan Giesselmann (Technische Universität Darmstadt, Germany)
Tabea Tscherpel (Technische Universität Darmstadt, Germany)

Port-Hamiltonian systems are becoming increasingly important in the modelling of physical systems. The key feature of this class of systems is the coupling of different subsystems using energy as the "lingua franca". Although obtaining structure preserving space discretizations is quite straightforward, structured time discretizations of pH systems are more challenging. For the latter, the main goal is to have an energy balance for the time-discrete system that resembles the energy balance of the original model. This is especially challenging for nonlinear systems.

The implications of classical time discretization schemes for the pH structure have been investigated in, e.g., [1, 2, 3]. Another recent approach uses discrete gradient pairs [4]. In this talk, we present a structure preserving scheme based on a Petrov-Galerkin-type procedure that is suitable for nonlinear systems. The approach is similar to that considered in [5] and uses a piecewise polynomial ansatz to approximate the trajectory of the pH system, which allows for an arbitrary order of convergence. We show that the scheme leads to the satisfaction of a discrete-time energy balance and present an a posteriori estimate for the approximation error. Finally, we illustrate the effectiveness of the approach with numerical examples.

[1] P. Kotyczka and L. Lefèvre, Discrete-time port-Hamiltonian systems: A definition based on symplectic integration, Systems & Control Letters, 133 (2019), p. 104530.
[2] V. Mehrmann and R. Morandin, Structure-preserving discretization for port-Hamiltonian descriptor systems, IEEE, 2019, pp. 11–13.
[3] R. Morandin, Modeling and numerical treatment of port-Hamiltonian descriptor systems, Doctoral Thesis, 2024.
[4] P. Schulze, Structure-preserving time discretization of port-Hamiltonian systems via discrete gradient pairs, arXiv preprint 2311.00403, 2023.
[5] H. Egger, O. Habrich, and V. Shashkov, On the energy stable approximation of Hamiltonian and gradient systems, Computational Methods in Applied Mathematics, 21 (2021), pp. 335–349.

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## System identification and dissipativity inference from input-output data

Kanat Camlibel (University of Groningen, The Netherlands)

This talk deals with two different issues: the identification of a dissipative system and the inference of dissipativity from given input-output data. More concretely, consider an *unknown* linear discrete-time input-state-output system

$$\begin{aligned} x(t+1) &= A_{\text{true}}x(t) + B_{\text{true}}u(t) \\ y(t) &= C_{\text{true}}x(t) + D_{\text{true}}u(t) \end{aligned}$$

where $A_{\text{true}} \in \mathbb{R}^{n_{\text{true}} \times n_{\text{true}}}$, $B_{\text{true}} \in \mathbb{R}^{n_{\text{true}} \times m}$, $C_{\text{true}} \in \mathbb{R}^{p \times n_{\text{true}}}$, and $D_{\text{true}} \in \mathbb{R}^{p \times m}$. We refer to this system as the *true system*. Let $(u_{[0,T-1]}, y_{[0,T-1]})$ be input-output data generated by the true system, i.e., there exists $x_{[0,T]} \in \mathbb{R}^{n_{\text{true}} \times (T+1)}$ such that

$$\begin{bmatrix} x_{[1,T]} \\ y_{[0,T-1]} \end{bmatrix} = \begin{bmatrix} A_{\text{true}} & B_{\text{true}} \\ C_{\text{true}} & D_{\text{true}} \end{bmatrix} \begin{bmatrix} x_{[0,T-1]} \\ u_{[0,T-1]} \end{bmatrix}.$$

In this talk, we address two questions: Under what conditions on the data $(u_{[0,T-1]}, y_{[0,T-1]})$,

(1) can we uniquely identify the true system if it is dissipative?
(2) can we infer dissipativity of the true system?

These seemingly unrelated questions turn out to be intimately intertwined. To unravel their relationship, we will first present novel necessary and sufficient conditions concerning system identification of linear systems from input-output data. As one might expect, system identification requires a certain rank condition on data Hankel matrices. What is truly remarkable, however, is that the depth of the Hankel matrix, which plays a pivotal role in determining whether the data are rich enough for system identification, depends *not only* on the prior knowledge of the system *but also* on the given data. As a side result, we will also provide the shortest possible experiment for linear system identification. Subsequently, we will delve into dissipativity theory within a behavioral framework by unleashing the language of quadratic difference forms to provide conditions for dissipativity solely in terms of input-output data. By merging these insights, we provide answers to the aforementioned questions and illuminate their interrelation.

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## Dissipativity Properties in Neural Network Training

Jens Püttschneider (TU Dortmund University, Germany)
Timm Faulwasser (TU Dortmund University, Germany)

System-theoretic dissipativity notions introduced by Jan C. Willems [1] play a fundamental role in the analysis of optimal control problems. They enable the understanding of infinite-horizon asymptotics and turnpike properties. Moreover, the training of neural networks can be formalized as an optimal control problem aiming at finding the weights and biases as control inputs to steer the data to a desired setpoint at the terminal layer [2]. Moreover, dissipativity concepts for neural networks have already been considered in Hamiltonian settings [3].

This talk introduces a dissipative formulation for training deep Residual Neural Networks (ResNets) for classification problems without considering the Hamiltonian setting. To this end, we formulate the training of ResNets with a constant width as an optimal control problem and investigate its dissipativity properties when introducing a stage cost based on a variant of the cross entropy loss function, the classic loss function for classification tasks [4]. Leveraging the dissipative formulation, we show that the trained networks exhibit the turnpike phenomenon: the data remains unchanged throughout several layers.

We illustrate the dissipative formulation by training on the MNIST dataset. Figure 4.1 shows the evolution of the data trajectories over the Layers of the ResNets for the two spirals classification task [5]. It illustrates

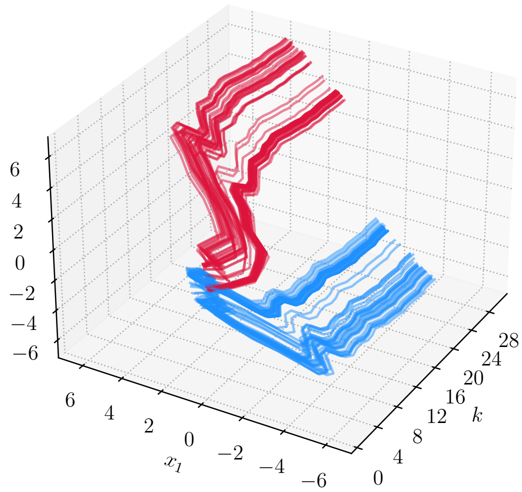



Figure 4.1: Evolution of the state trajectories for the two classes of the two spirals dataset exhibiting the turnpike property.

how the datapoints of the two classes are initially separated in the first ten layers of the network and afterward remain constant, showing the turnpike phenomenon. These layers can then be removed without changing the transformation learned by the NN. This technique can be used to obtain shallow neural networks for a given classification task with simplified hyperparameter tuning.


[1] J. C. Willems. Dissipative dynamical systems part I: General theory. *Archive for rational mechanics and analysis*, 45.5: 321-351, 1972.

[2] C. Esteve, B. Geshkovski, D. Pighin, and E. Zuazua. Large-time asymptotics in deep learning. *arXiv preprint arXiv:2008.02491*, 2020.

[3] C. L. Galimberti, L. Furieri, L. Xu, and G. Ferrari-Trecate. Hamiltonian deep neural networks guaranteeing non-vanishing gradients by design. *IEEE Transactions on Automatic Control*. 2023.

[4] J. Püttschneider, and T. Faulwasser. A Dissipative Formulation for Training ResNets with Cross-Entropy Loss. *In preparation*

[5] K. J. Lang and M. J. Witbrock. Learning to tell two spirals apart. *1988 connectionist models summer school*, pp. 52–59, 1988.

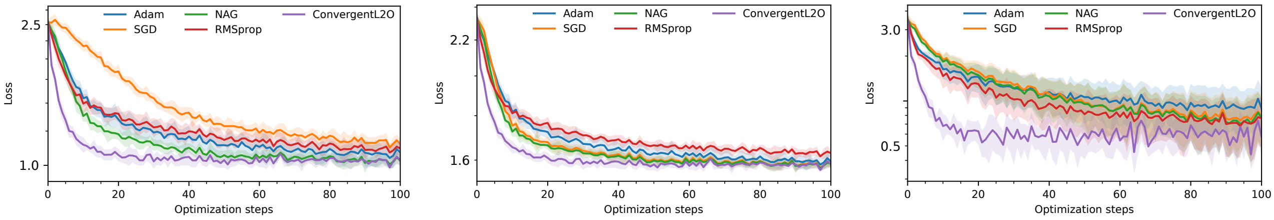

## Learning to optimize with convergence guarantees[1]


Furieri Luca (EPFL, Switzerland)
Martin Andrea (EPFL, Switzerland)


Control theory has increasingly interpreted iterative update rules as evolving discrete-time dynamical systems. Notably, [1, 2] and references therein utilize dissipativity approaches to synthesize algorithms with optimized convergence rates for classes of convex functions. Moving towards the prevalent non-convex case, we propose methods to design iterative optimization algorithms that inherently converge to a critical point $\hat{x}$ such that $\nabla f(\hat{x}) = 0$ for all non-convex smooth objective functions $f(\cdot)$. In line with emerging Learning to Optimize (L2O) approaches [3], we adopt customizable algorithm performance metrics that can, for instance, blend algorithmic speed and the quality of the solutions they converge to, as specified by the user.

[1]Arxiv preprint available at `https://arxiv.org/abs/2403.09389`. Code for numerical examples available at `https://github.com/andrea-martin/ConvergentL2O`.

Our key contribution is the reformulation of the problem of learning optimal convergent algorithms into an equivalent, unconstrained one that is directly amenable to automatic differentiation tools. We achieve this by dividing update rules into: 1) a gradient descent step that ensures convergence, and 2) an innovation term that, by learning to react to the current and past values of $x_t$, $\nabla f(x_t)$, and $f(x_t)$, enhances performance without compromising convergence. Notably, our method encompasses *all and only* convergent algorithms, thus sidestepping conservatism. Furthermore, we guarantee convergence of the learned algorithm even when dealing with noisy and incomplete gradient measurements, thus making our methodology relevant for machine learning with batch data.




(a) tanh. (b) sigmoid. (c) ReLU.

Figure 4.2: Optimizer performance for different activation functions

Figure 4.2 compares the performance of our learned optimizer with standard neural network training algorithms (Adam, NAG, RMSprop, SGD), on the task of optimizing a shallow neural network for image classification with the MNIST dataset. By training over networks with tanh activation functions and testing on ones with ReLU, our results corroborate the transfer learning capabilities of L2O to tasks structurally different from those in training. As predicted by our theoretical results, none of our simulations exhibited the divergence phenomena reported in the L2O literature [3].

Towards an increasingly cohesive integration of algorithms with closed-loop cyber-physical systems, further avenues for future research include extending our framework to online and time-varying scenarios, distributed and federated learning, and constrained optimization.


[1] L. Lessard, B. Recht, A. Packard. Analysis and design of optimization algorithms via integral quadratic constraints. In SIAM Journal on Optimization, volume 26, number 1, pages 57–95, 2016.

[2] C. Scherer, C. Ebenbauer. Convex synthesis of accelerated gradient algorithms. In SIAM Journal on Control and Optimization, volume 59, number 6, pages 4615–4645, 2021.

[3] T. Chen, X. Chen, W. Chen, H. Heaton, J. Liu, Z. Wang and W. Yin- Learning to optimize: A primer and a benchmark. In Journal of Machine Learning Research, volume 23, number 189, pages s1–59, 2022.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## Unconstrained learning of networked nonlinear systems via free parametrization of stable interconnected operators


Leonardo Massai (EPFL, Switzerland)

Danilo Saccani, Luca Furieri, Giancarlo Ferrari-Trecate (EPFL, Switzerland)


This paper characterizes a new parametrization of nonlinear networked incrementally $L_2$-bounded operators in discrete time. The distinctive novelty is that our parametrization is *free* – that is, a sparse large-scale operator with bounded incremental $L_2$ gain is obtained for any choice of the real values of our parameters. Based on the dissipativity of interconnected systems [3], this property allows one to freely search over optimal parameters via unconstrained gradient descent, enabling direct applications in large-scale optimal control and system identification. Further, we can embed prior knowledge about the interconnection topology and stability properties of the system directly into the large-scale distributed operator we design. Our approach is extremely general in that it can seamlessly encapsulate and interconnect state-of-the-art Neural Network (NN) parametrizations of stable dynamical systems.

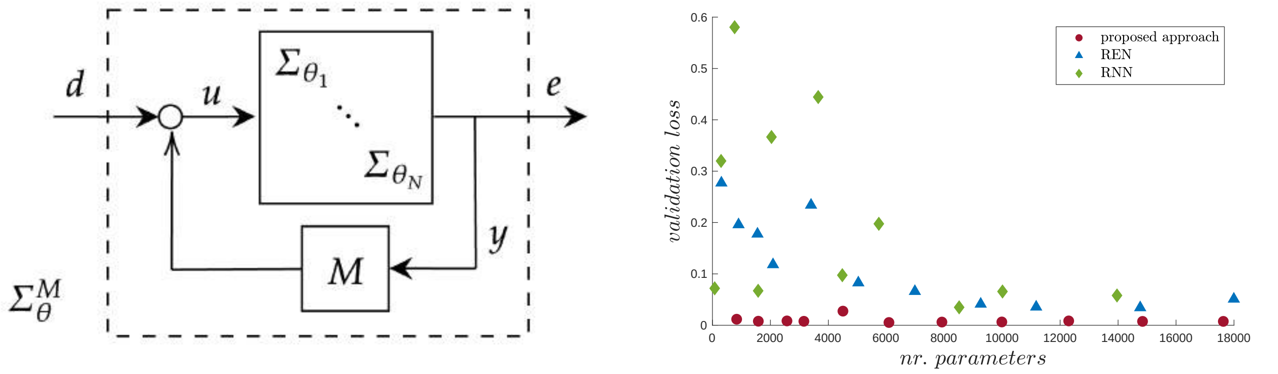


Figure 4.3: (Left) Interconnection of $N$ RENs operators $\Sigma_{\theta_i}$. (Right) Comparison of validation loss as a function of tunable parameters is conducted for the proposed approach with three RENs (red " ○ "), a single REN (blue " △ "), and a Recurrent Neural Network RNN (green " ◇ "). Notably, the single REN and the RNN disregard the network topology.

To demonstrate the effectiveness of this approach, we provide a simulation example showcasing the identification of a networked nonlinear system by means of an interconnected Recurrent Equilibrium Networks (RENs) [2]. Figure 4.3 (left) depicts the interconnection considered for the system of RENs, mimicking the interconnection of the networked system under consideration for identification. In Figure 4.3 (right), the simulation results of the system identification task underscore the superiority of our free parametrizations over standard NN-based identification methods, where a prior over the system topology and local stability properties are not enforced. The proposed approach may open up several venues for future research, including application of these operators as distributed controllers, mirroring the sparsity pattern of the plant, holds promise for enhancing closed-loop properties based on dissipativity theory.


[1] Arcak, Murat and Meissen, Chris and Packard, Andrew Networks of dissipative systems: compositional certification of stability, performance, and safety. Springer, 2016.

[2] Revay, Max and Wang, Ruigang and Manchester, Ian R Recurrent equilibrium networks: Flexible dynamic models with guaranteed stability and robustness. IEEE Transactions on Automatic Control, 2023.


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## Neural Distributed Controllers with Port-Hamiltonian Structures


Muhammad Zakwan (EPFL, Switzerland)
Giancarlo Ferrari-Trecate (EPFL, Switzerland)


Controlling large-scale cyber-physical systems necessitates optimal distributed policies, relying solely on local real-time data and limited communication with neighboring agents. However, finding optimal controllers remains challenging, even in seemingly simple scenarios. Parameterizing these policies using Neural Networks (NNs) can deliver state-of-the-art performance, but their sensitivity to small input changes can destabilize the closed-loop system. This paper addresses this issue for a network of nonlinear dissipative systems. Specifically, we leverage well-established port-Hamiltonian structures to characterize deep distributed control policies with closed-loop stability guarantees and a finite $\mathcal{L}_2$ gain, regardless of specific NN parameters. This eliminates the need to constrain the parameters during optimization and enables training with standard methods like stochastic gradient descent. A numerical study on the consensus control of Kuramoto oscillators demonstrates the effectiveness of the proposed controllers.

The main contributions of this paper can be summarized as follows:

1. We provide a free parameterization of distributed controllers that can seamlessly incorporate sparsity in their weight matrices and are inherently endowed with a finite $\mathcal{L}_2$ gain.
2. Our approach overcomes the limitation of being restricted to specific storage functions (e.g., quadratic), enabling its application to a broader range of nonlinear control problems.
3. We demonstrate the efficacy of our learning-enabled controllers on a benchmark consensus problem for Kuramoto oscillators.

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## Learning Stabilizing Distributed Optimal Control for Nonlinear Systems through Neural Closed-Loop Maps

Danilo Saccani (EPFL, Switzerland)
Leonardo Massai, Luca Furieri, Giancarlo Ferrari-Trecate (EPFL, Switzerland)

Controlling interconnected systems with non-linear dynamics can be difficult. Maintaining stability while achieving optimal performance becomes increasingly challenging as the complexity of the system grows. This paper proposes a novel approach to improve the performance of distributed control systems by leveraging Deep Neural Networks (DNNs). We build upon the Neural System Level Synthesis (Neur-SLS) framework [1] and dissipativity theory of networked systems [3] to introduce a method to parameterize stabilizing control policies that are distributed across a network topology. A distinctive feature is that we iteratively minimize an arbitrary control cost function through unconstrained automatic differentiation, all while preserving stability of the overall network architecture by design. This is achieved through two key steps. First, we establish

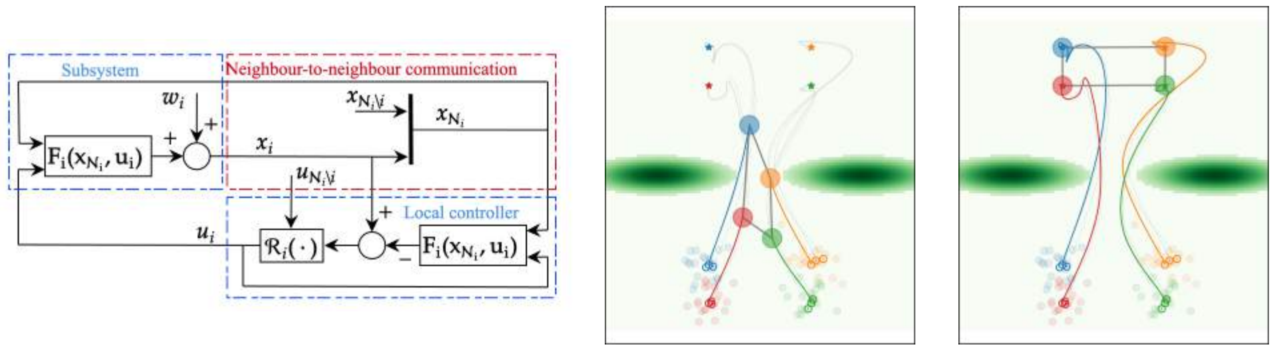


Figure 4.4: (Left) Considered parametrization of stabilizing distributed controllers in terms of one freely chosen non-linear $l_p$-stable operator. (Right) Closed-loop trajectories after training over randomly sampled initial conditions marked with "∘". Colored spheres (and their radius) represent the agents (and their size for collision avoidance).

a method to parameterize interconnected Recurrent Equilibrium Networks (RENs) [2] that guarantees a bounded $L_2$ gain at the network level. This ensures stability. Second, we demonstrate how information flow within the network is preserved, enabling a fully distributed implementation where each subsystem only communicates with its neighbors. To showcase the effectiveness of our approach, we validate our results by considering a fleet of 4 mobile robots that need to keep a formation on the $xy$-plane, avoiding the obstacles while preserving stability of the closed loop at all iterations of the training. The robots can only rely on neighbors' information, must avoid collisions between each other, and their trajectories should minimize a given nonlinear loss function. Figure 4.4 (left) illustrates the considered parametrization of the stabilizing controllers. Figure 4.4 (right) shows the closed-loop trajectories of the fleet after training.


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## Various representations of Boundary Port Hamiltonian Systems


Bernhard Maschke (Université Claude Bernard Lyon 1, France)


In this talk we shall present an overview and some perspectives on various recent port-Hamiltonian formulation of Distributed Parameter Systems. In a first part we shall recall the definition of Boundary Port Hamiltonian Systems, where the interface variables of the systems at its boundary, the boundary port variables, are derived from a canonical extension of a Hamiltonian operator to an associated Dirac structure [4]. This Dirac structure is defined over the Pontryagin bundle, the product of the tangent and co-tangent bundle augmented with the product of two dual spaces, defining the boundary port variables. For physical systems the product of dual port variables has the dimension of power. In the second part, we shall present the recent extension of Boundary port-Hamiltonian systems to the case when their state space is a Lagrange subspace defined by reciprocal differential operators [1, 2]. These reciprocal operators correspond to the definition of the constitutive relations defining the relation between the energy variables (the extensive varables) and the co-energy variables (the intensive variables) of physical systems. In this case, some additional boundary variables have to be considered and may be derived in a canonical way from the reciprocal operators. In the third part, we shall consider various possible representations of physical systems, in particular the relation between the symplectic formulation of elasto-dynamical systems where the energy is given by possibly non-local elasticity relations, and their extension on a higher-dimensional state space where the energy is given by a function [2, 3]. We shall conclude with some remaining open problems and perspectives.


[1] B. Maschke and A.J. van der Schaft. Linear Boundary Port Hamiltonian systems defined on Lagrangian submanifolds. *IFAC-PapersOnLine*, 53(2):7734–7739, 2020. 21th IFAC World Congress.

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[3] T. Preuster, M. Schaller, and B. Maschke. Jet space extensions of infinite-dimensional Hamiltonian systems. *arXiv preprint arXiv:2401.15096*, 2024.

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## Jet space extensions of infinite-dimensional Hamiltonian systems

Till Preuster (Technische Universität Ilmenau, Germany)
Bernhard Maschke (Université Claude Bernard Lyon 1, France)
Manuel Schaller (Technische Universität Ilmenau, Germany)

Boundary port-Hamiltonian systems are an energy-based approach to model the dynamics of distributed parameter systems on one-dimensional spatial domains. These systems are defined by a formally skew-symmetric Hamiltonian differential operator and a Hamiltonian energy function. In various applications appearing in fluid dynamics or mechanics, the Hamiltonian function depends on spatial derivatives of the state. Due to the corresponding strong intertwinement of energy-storing components modeled by a Stokes-Lagrange structure, and energy-routing elements modeled by a Stokes-Dirac structure, the derivation of port-variables is not straightforward and a geometric description is particularly challenging. In this talk, we present a method to reformulate the dynamics such that the energy functional depends on the state variable only, and not on its spatial derivatives. To this end, we embed the system into the higher-dimensional jet space. As a consequence, a geometric description may be given by a Stokes-Dirac structure and a Lagrange subspace. We illustrate our approach by means of various examples including an elastic rod and the Boussinesq equation. This is joint work with Manuel Schaller (TU Ilmenau) and Bernhard Maschke (U Lyon) and based on [1].

[1] T. Preuster, M. Schaller, B. Maschke. Jet space extensions of infinite-dimensional Hamiltonian systems. *Proceedings of 8th IFAC Workshop on Lagrangian and Hamiltonian Methods for Nonlinear Control*, to appear, 2024.

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## Homogenization and optimization of eigenvalues of dissipative Maxwell systems

Illia Karabash (IAM, the University of Bonn, Germany)

The homogenization of eigenvalues of non-Hermitian Maxwell operators will be considered with the help of the H-convergence method. The Maxwell system is assumed to be equipped with m-dissipative boundary conditions defined via impedance operators and suitable boundary tuples. We found wide classes of Leontovich and, more generally, generalized impedance boundary conditions having the property that nonzero spectra of associated m-dissipative Maxwell operators are discrete. We prove the convergence of eigenvalues to an eigenvalue of a homogenized Maxwell operator under the assumption of the H-convergence of the material parameters and, as a by-product, we obtain the existence of an eigenvalue-free region around zero. These results are applied to a spectral optimization problem coming from quantum optics. If time allows us, connections with unique and nonunique continuation properties for Maxwell equations will be also discussed.

The talk is based on the joint papers with Matthias Eller [1, 2].

[1] M. Eller and I.M. Karabash. M-dissipative boundary conditions and boundary tuples for Maxwell operators. *Journal of Differential Equations*, 325:82–118, 2022. https://doi.org/10.1016/j.jde.2022.04.006
[2] M. Eller and I.M. Karabash. Homogenization and nonselfadjoint spectral optimization for dissipative Maxwell eigenproblems, *arXiv preprint arXiv:2401.01049 [math.AP]*, 31 p., 2024. https://doi.org/10.48550/arXiv.2401.01049

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## On the port-Hamiltonian structure of interacting particle systems

Claudia Totzeck (University of Wuppertal, Germany)
Birgit Jacob (University of Wuppertal, Germany)

The port-Hamiltonian structure of interacting particle sytems allows to analyse the long-term behaviour such as flocking and clustering. Based on the preprint [1] we discuss the port-Hamiltonian structure underlying interacting particle systems with general alignment and potential interactions and show how this structure allows to analyse the long-time behaviour of the system with a La Salle-type argument. Then we see that the port-Hamiltonian structure is preserved in the mean-field limit and that a La Salle-type result in infinite dimensions allows to characterise the long-time behaviour of the mean-field dynamics.

[1] B. Jacob, C. Totzeck (2023) Port-Hamiltonian structure of interacting particle systems and its mean-field limit *preprint*, arxiv:2301.06121, 2023.

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## Passivity-preserving model reduction of quasilinear magneto-quasistatic feld problems

Tatjana Stykel (Universität Augsburg, Germany)

Johanna Kerler-Back (ESG Elektroniksystem- und Logistik-GmbH, Germany)
Timo Reis (Technische Universität Ilmenau, Germany)

We consider quasilinear magneto-quasistatic (MQS) field equations which arise in simulation of low-frequency electromagnetic devices coupled to electrical circuits. By defining suitable Dirac and resistive structures, such equations admit a representation as a port-Hamiltonian system [1]. A finite element discretization of the MQS model on 3D domains leads to a singular system of differential-algebraic equations (DAEs). First, we study the structural properties of this system and present a new regularization approach based on projecting out the singular state components. Furthermore, we investigate the passivity of the variational MQS problem and semidiscretized system by defining appropriate storage functions. For model reduction of the quasilinear MQS system, we use the proper orthogonal decomposition (POD) technique combined with the discrete empirical interpolation method (DEIM) for fast evaluation of the nonlinearity. Our model reduction approach is based on transforming the regularized DAE into a system of ordinary differential equations by exploiting a special block structure of the underlying problem and applying standard model reduction methods to the resulting system. For the POD reduced model, we prove the preservation of passivity, while for the POD-DEIM reduced model, we present a passivity enforcement method based on a perturbation of the output which depends on DEIM errors. Numerical experiments demonstrate the performance of the presented model reduction methods and the passivity enforcement technique.

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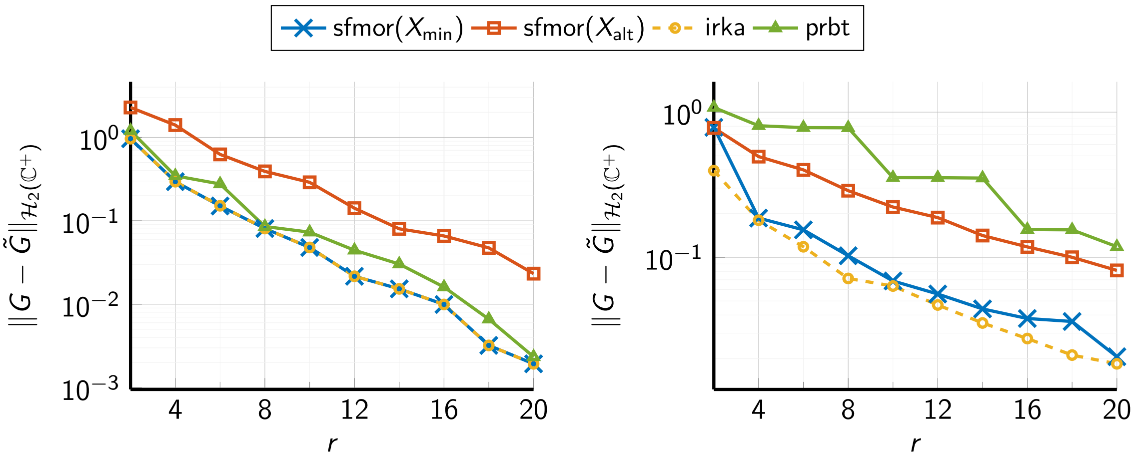
# Passivity-preserving model reduction for passive descriptor systems

Benjamin Unger (University of Stuttgart, Germany)
Steffen Müller (University of Stuttgart, Germany)

With the increasing interest in port-Hamiltonian descriptor systems, structure-preserving variants of well-established model order reduction methods must be developed for efficient simulation, parameter studies, analysis, and control. In the linear time-invariant non-descriptor case, it was recently demonstrated that passivity and, thus, the port-Hamiltonian structure can be preserved by performing model reduction on a spectral factor of the system [1]. A reduced passive system exhibiting this spectral factor can be constructed whenever the reduced spectral factor is asymptotically stable. Besides asymptotic stability, no further structure of the spectral factor has to be preserved such that classical methods such as balanced truncation or IRKA can be used, and numerical experiments demonstrate that this method frequently outperforms positive-real balanced truncation [2] and the port-Hamiltonian structure-preserving variant of IRKA [3]. In this talk, we extend the spectral factor model reduction approach to passive descriptor systems [5] and discuss the optimal choice of the spectral factor. For several numerical examples, see for instance Figure 4.5, we demonstate that our method outperforms existing methods. If time permits, we discuss open questions regarding the optimal choice of the Hamiltonian in the reduced model [4].




(a) `RCL-1-SISO` (b) `RCL-1-MIMO`

Figure 4.5: $\mathcal{H}_2$-errors for different model reduction methods and different reduced dimensions.

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[2] U. Desai and D. Pal. A transformation approach to stochastic model reduction. IEEE Trans. Automat. Control, 29(12):1097–1100, 1984.
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## Singular operator pencils

Michał Wojtylak (Jagiellonian University, Poland)
Christian Mehl (TU Berlin, Germany)
Volker Mehrmann (TU Berlin, Germany)

We provide a systematic theory of singular pencils $\lambda E - A$, with (possibly unbounded) operator coefficients in a Hilbert space. Apparently, the situation is more complicated than in the finite dimensional case. Several equivalent statements connected to the Kronecker canonical form become essentially different when the dimension is infinite. We show the relation of these concepts to solvability of the corresponding (infinite dimensional) differential-algebraic equations $E\dot{x} = Ax$.

While the general theory is rather complicated, it essentially simplifies for the operator pencils of type

$$\lambda E - (J - R),$$

where $E, R$ are positive semidefinite, $J$ is skew-symmetric. Here the results are analogous to the finite dimensional situation, discussed in the references below.

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[2] C. Mehl, V. Mehrmann and M. Wojtylak. Distance problems for dissipative Hamiltonian systems and related matrix polynomials. *Linear Algebra and its Applications*, 623, 335-366.

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## Incremental dissipativity and its application in optimization-based state estimation

Matthias A. Müller (Leibniz University Hannover, Institute of Automatic Control, Germany)
Julian D. Schiller (Leibniz University Hannover, Institute of Automatic Control, Germany)

Incremental dissipativity essentially connects incremental input-output properties to incremental Lyapunov stability. Since this property is defined with respect to arbitrary pairs of trajectories (and not in relation to a single point of minimum storage), it allows to derive global stability and performance guarantees for general nonlinear dynamical systems, cf. [1, 2].

In this talk, we discuss a variant of incremental dissipativity that is particularly useful in the context of state estimation, i.e., for the case where the internal state of a dynamical system is unknown and needs to be reconstructed. In particular, by including an additional strictness term in the incremental supply rate with respect to the internal states, we effectively introduce an incremental form of strict (internal-state) dissipativity that entails an asymptotic distinguishability property of states based on past input/output data. In fact, this dissipativity property corresponds to a Lyapunov characterization of incremental input/output-to-state stability, which is necessary for the existence of robustly stable state estimators, cf. [3]. Moreover, we show how the strong connection of incremental dissipativity to contraction theory allows the application of simple tools to verify the required dissipation inequality in practice using quadratically bounded storage functions, cf. [4, 5]. The proposed method relaxes the typical requirements when using established tools for verifying incremental dissipativity (such as, e.g., [2]), which fail in this application due to the generic supply rate considered here.

In the second part of this talk, we show how the above strict incremental dissipativity property directly leads to guarantees for optimization-based state estimation, in particular, moving horizon estimation (MHE). Such methods are naturally applicable to estimate the internal states of nonlinear, potentially constrained systems and have applications in various fields, such as chemical and process engineering, biomedical engineering and systems medicine, robotics, and power systems. We illustrate that choosing the MHE cost function based on the storage function and supply rate characterizing the incremental dissipativity property directly translates into strong robustness guarantees for MHE. This leads to practically relevant conditions for the design of nonlinear MHE schemes, cf. [4, 5].

In the last part of the talk, we discuss under which conditions the presented MHE framework can be applied to joint state and parameter estimation. This essentially requires the incremental dissipation inequality to be defined only along certain pairs of (persistently excited) trajectories. However, since one of the trajectories involved is always unknown during operation, we propose a procedure to online verify the dissipation inequality using data from only one of the trajectories involved, cf. [6].


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## Strict Dissipativity for Economic Model Predictive Control of District Heating Networks: Challenges and Solutions


Max Sibeijn (TU Delft, The Netherlands)
Saeed Ahmed (Groningen University, The Netherlands)
Mohammad Khosravi (TU Delft, The Netherlands)
Tamas Keviczky (TU Delft, The Netherlands)


District heating networks (DHN) play an integral role in the transition towards a sustainable future, utilizing renewable and reusable energy resources. These networks are governed by complex nonlinear dynamics, involving PDEs for hydraulic and thermal transport of heated water. Historically, decentralized rule-based controllers [1] were used to manage DHN, with limited communication between central heat stations, substations, and consumers. However, as DHN continue to expand in scale and incorporate multiple producers, control systems will need to become more sophisticated. Additionally, leveraging the thermal inertia of network buffers will be crucial for mitigating congestion on the electricity grid.

Economic model predictive control (MPC) is a promising method that can suitably capture the time-varying nature of DHN by using predictions to generate optimal set points for the actuators of the network. This can significantly increase economic gain and improve system operation. Economic MPC is a widely studied technique for energy system control. However, it is a generalization of tracking MPC, and therefore, it does not share the same closed-loop guarantees as tracking MPC [2].

In this work, we study the application of economic MPC to DHN. Specifically, we formulate a graph-based modeling framework that can incorporate multiple producers and storage, similar to [3] and [4], and that is suitable for optimization-based control. Furthermore, we establish conditions under which the nonlinear dynamical system is strictly dissipative with respect to the MPC stage cost and an optimal equilibrium point, both using analytical and numerical methods (sum of squares programming) [5]. Strict dissipativity is a sufficient condition for the turnpike property, which in turn grants closed-loop convergence and optimality guarantees for the economic MPC. Nonetheless, we also discuss limitations and challenges related to searching for dissipative structures in this context. Ultimately, our aim is to capitalize on the flexibility of time-varying elements, such as electricity pricing and heat demand, to enhance the DHN's efficiency. Although simulations suggest turnpike-like behavior, translating the time-varying problem into a compatible form that admits strict dissipativity proves to be a challenge.

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## Causality Structures in Stochastic Optimal Control

Timm Faulwasser (TU Hamburg, Germany)
Ruchuan Ou (TU Dortmund, Germany)

Causality plays a fundamental role in stochastic control problems. Essentially, it requires that current control actions do not depend on uncertainty realizations yet to happen. In this talk, we take a fresh look at optimal control problems for discrete-time systems subject to stochastic disturbances of finite variance. We formulate these problem using polynomial chaos expansions (PCE), which rely on Hilbert space properties of $L_2$ probability spaces. We show how the PCE framework allows to formulate in a straight-forward manner as a sparsity constraints. We discuss how one may exploit these causality conditions in numerical solution of optimal control problems. We present novel error bounds for PCE bases of finite length [1] and we sketch the link of our findings to dissipativity notions.

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## Dissipativity and Turnpike in Stochastic Optimal Control

Jonas Schießl (University of Bayreuth, Germany)
Ruchuan Ou (TU Dortmund University, Germany)
Michael H. Baumann (University of Bayreuth, Germany)
Timm Faulwasser (TU Dortmund University, Germany)
Lars Grüne (University of Bayreuth, Germany)

Since its introduction by Jan C. Willems [8], the concept of dissipativity has become a valuable tool for analyzing optimal and model predictive control problems. While dissipativity and its relationship to the so-called turnpike property are well-established for deterministic problems [1, 2, 4, 5], their extension to stochastic settings requires further theoretical development.

In this talk, we introduce different notions of dissipativity based on stationarity concepts in distribution and random variables. Using recent results [6], we show that these notions are suitable for analyzing the distributional and the pathwise behavior of stochastic problems, which distinguishes our approach from the measure-based one presented in [3]. Moreover, we highlight the connection between our stochastic dissipative concepts and different stochastic turnpike properties. The proposed turnpike properties are each associated with a different metric to measure the distance between the optimal stationary solutions of the problem and range from a formulation for random variables via turnpike phenomena in probability and in distribution to a turnpike property for single moments.

In order to illustrate our theoretical findings, we consider the generalized linear-quadratic stochastic optimal control problem for which stochastic dissipativity can be shown by explicitly constructing a proper storage function [7]. Moreover, we visualize the several stochastic turnpike properties presented by numerical simulations.


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## Passivity-based Control of DC-DC Boost Converters


Morteza Nazari Monfared (University of Pavia, Italy)
Yu Kawano (Hiroshima University, Japan)
Michele Cucuzzella (University of Groningen, the Netherlands)


Passivity theory provides powerful tools for analyzing nonlinear systems [8]. This theory is continuously expanding through introduction of new passivity notions such as equilibrium independent passivity [9] and incremental passivity [1]. Over recent years, two novel passivity notions have introduced: Krasovskii passivity [6] and differential passivity [10]. The former is established upon Krasovskii's Lyapunov function for stability analysis [5], while the latter is rooted in the differential Lyapunov theory or contraction analysis [3]. The connection between standard, shifted, incremental, krasovskii and differential passivities are well explored in [4]. The differential passivity is considered as the passivity property of the variational system. Not only do the passivity notions provide deeper insights into system analysis, but they also enables designers to design nonlinear controllers to attain diverse control objectives for various systems [2, 6, 7].

In this presentation, we revisit the introduced controller in the authors' recent publication [7], in terms of differential passivity property. More precisely, we demonstrate that the presented controller in [7] can be developed based on holding passivity property of the system. Then, by invoking the LaSalle invariance principle for contraction analysis [3], we establish the incremental asymptotic stability of the closed-loop system.

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## Predictive Path-Following based on Manifold Turnpikes and Dissipativity


Mohammad Itani (TU Hamburg, Germany)
Timm Faulwasser (TU Hamburg, Germany)


Path-following problems concern the design of controllers that force the output of a system to follow a geometric reference path without requiring an a priori time-parameterization of the movement on the path. That is, in path-following, the assignment *when to be where* on the reference is made at run-time of the controller and not a priori. Path-following ideas can be combined with Nonlinear Model Predictive Control (NMPC) [1]. The main advantage of utilizing this combination compared to other methods is its natural ability to account for system constraints.

Under certain geometric conditions, solving a path-following problem is equivalent to the stabilization of a manifold in the state space – the so-called path manifold [1], [5]. In this paper, we present a NMPC scheme without terminal constraints, yet with guaranteed practical convergence to the path manifold. The novelty of our scheme lies in the exploitation of the manifold turnpike property [2] to prove the convergence of the scheme. Put differently, the proposed scheme links recent developments on dissipativity-based analysis of optimal control problems [3] and of economic predictive control schemes [4] with the geometric analysis of path-following problems for nonlinear systems.


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## Port-Hamiltonian perspectives in modeling and control of multi-energy networks

Hannes Gernandt (University of Wuppertal, Germany)

In this presentation, we highlight various applications of port-Hamiltonian and dissipativity-based modeling and control within the context of multi-energy networks.
In the first part, we introduce a port-Hamiltonian (pH) modeling approach for switching power systems [1], demonstrating how the inherent port-Hamiltonian structure facilitates stabilizing control design. These findings are illustrated by analyzing a network of charging stations for electric vehicles.
Moving on to the second part, we discuss a dissipativity-based modeling approach applied to 4th and 5th generation district heating grids [3]. These complex systems include numerous distributed power-to-heat devices, such as heat pumps, which naturally leads to sector-coupled electrothermal systems. After formulating the continuous-time model, we employ a dissipativity-preserving discretization and apply a stabilizing model-predictive control (MPC) scheme. The findings are illustrated using a small-scale example of a heating network.
Finally, we deal with distributed parameter networks, derived from the previously discussed systems by replacing models for electric transmission lines or transmission pipes with partial differential equation (PDE) models. Within this class of distributed pH networks, we present results on passivity and stability [2].

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## Recent progress on the EPHS modeling language: Multibody systems and discrete-time semantics

Markus Lohmayer (FAU, Germany)
Owen Lynch (Topos, USA)
Giuseppe Capobianco (FAU, Germany)
Sigrid Leyendecker (FAU, Germany)

The recently formalized modeling language termed Exergetic Port-Hamiltonian Systems (EPHS) provides a user-friendly and mathematical basis for compositional modeling of multiphysical systems [1]. A large class of models including mechanics, electromagnetism and irreversible processes with local thermodynamic equilibrium can be expressed as EPHS. Based on a graphical syntax, models can be easily composed from simpler parts. Three kinds of primitive models respectively represent energy storage and reversible/irreversible energy exchange. The storage function of a composite EPHS is the available energy of all its storage components and the dynamics of reversible/irreversible components is lossless/dissipative. Structural properties ensure thermodynamic consistency as known from the GENERIC/metriplectic formalism. In this talk, we give an overview on two threads of ongoing work. The first one explores a possible application, namely systems of rigid bodies connected by joints [2]. The second thread leads to a discrete-time semantics for spatially-lumped EPHS, which admits a variational structure and is related to the continuous-time semantics by a natural transformation. Naturality here means that discretization and interconnection are compatible, i.e. they commute.


[1] M. Lohmayer, O. Lynch, S. Leyendecker. Exergetic Port-Hamiltonian Systems Modeling Language http://doi.org/10.48550/ARXIV.2402.17640, 2024

[2] M. Lohmayer, G. Capobianco, S. Leyendecker. Exergetic Port-Hamiltonian Systems for Multibody Dynamics. http://doi.org/10.48550/ARXIV.2402.18095, 2024


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## Relationships between dissipativity concepts for linear time-varying port-Hamiltonian systems


Dorothea Hinsen (Technische Universität Berlin, Germany)
Karim Cherifi (Technische Universität Berlin, Germany)
Hannes Gernandt (Bergische Universität Wuppertal, Germany)
Volker Mehrmann (Technische Universität Berlin, Germany)
Riccardo Morandin (Technische Universität Berlin, Germany)


Extending to complex values what is presented in [2, 4] a linear time-varying *port-Hamiltonian* system is a dynamical system of the form

$$\begin{aligned} \dot{x}(t) &= (J(t) - R(t)Q(t) - K(t))x(t) + (G(t) - P(t))u(t), \\ y(t) &= (G(t)^H + P(t)^H)Q(t)x(t) + (S(t) - N(t))u(t), \end{aligned}$$

where $Q \in W^{1,1}_{\mathrm{loc}}(\mathbb{T}, \mathbb{C}^{n,n})$, $J, R, K \in L^1_{\mathrm{loc}}(\mathbb{T}, \mathbb{C}^{n,n})$, $G, P \in L^2_{\mathrm{loc}}(\mathbb{T}, \mathbb{C}^{n,m})$ and $S, N \in L^\infty_{\mathrm{loc}}(\mathbb{T}, \mathbb{C}^{m,m})$ are such that $J(t) = -J(t)^H$, $N(t) = -N(t)^H$, $Q(t) = Q(t)^H \geq 0$, and

$$Q(t)K(t) + K(t)^H Q(t) = \dot{Q}(t),$$

as well as

$$W(t) := \begin{bmatrix} R(t) & P(t) \\ P(t)^H & S(t) \end{bmatrix} = W(t)^H \geq 0,$$

for a.e. $t \in \mathbb{T}$, together with a (time-varying) quadratic Hamiltonian $\mathcal{H}(t, x) = \frac{1}{2} x^H Q(t) x$ . In this talk, we study the relationship between passivity, having a nonnegative supply, and port-Hamiltonian representations for continuous-time linear time-varying systems. The previous results are surveyed and the subtle differences between the concepts are analyzed in detail [1, 3]. Furthermore, the connection to positive semidefinite solutions of the Kalman-Yakubovich-Popov inequality is investigated.


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# Finite-time output consensus for a network of nonlinear agents: Krasovskii and shifted passivity

Vaibhav Kumar Singh (University of Groningen, The Netherlands)
Yu Kawano (Hiroshima University, Japan)
Juan E. Machado (Brandenburg University of Technology C-S, Germany)
Michele Cucuzzella (University of Groningen, The Netherlands)
Jacquelien M.A. Scherpen (University of Groningen, The Netherlands)

Motivated by applications in power networks, heating ventilation and air-conditioning (HVAC) systems, a new notion of passivity has been presented in [1] for nonlinear systems. This new notion, referred to as Krasovskii passivity, establishes the dissipativity of a nonlinear system using an appropriate storage function and a supply rate that depends on the derivative of the input and output of the system. The properties of Krasovskii passive nonlinear system have been investigated in [2] and its relationship with various existing notions of passivity has been presented along with controller design techniques for the stability of input-affine nonlinear systems.

One of the real-world examples of nonlinear systems that are Krasovskii passive include DC microgrids. In the presence of unknown load current and power demand, it is difficult to model the DC microgrid as a port-Hamiltonian system which makes it problematic to exploit the conventional passivity properties for solving the grid problems like proportional current sharing and voltage regulation. To overcome this challenge, the Krasovskii passivity of the DC grid has been established in [3] where the authors have also solved a class of output consensus problem for Krasovskii passive and shifted passive nonlinear systems. The consensus protocols in [3] are asymptotic in nature i.e., the output of the nonlinear system converges to a consensus value asymptotically. Owing to various practical reasons, it is important to construct controllers that can guarantee consensus in a multi-agent network in a finite time. In this regard, multiple works have been reported in the literature on finite-time, fixed-time, and prescribed-time consensus of linear and non-linear multi-agent systems under various assumptions, see [4]. The focus of our work is to investigate the construction of distributed output-feedback controllers that can guarantee output consensus for a class of passive nonlinear systems while ensuring faster convergence time to the consensus value.

We consider a multi-agent system comprising $N$ heterogeneous agents with physical interconnection between each other through $M$ dynamical systems. The dynamics of each agent in the network is modeled by nonlinear systems with $m$ inputs and $m$ outputs. We consider two cases. For the first case, we assume that the nonlinear systems are Krasovskii passive and each agent dynamics is influenced by a constant disturbance. For the second case, we suppose that the nonlinear systems are shifted passive and each agent dynamics is injected with a time-varying external disturbance. Under these settings, we explore the construction of distributed continuous output-feedback controllers that can guarantee output consensus in the network and ensure that the convergence time to the consensus trajectory has a finite upper bound that may depend on the initial conditions of the system.

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# 5 List of Participants

| | |
|---|---|
| Çamlıbel, Kanat | University of Groningen, The Netherlands |
| Faulwasser, Timm | TU Dortmund and TU Hamburg, Germany |
| Furieri, Luca | EPFL, Switzerland |
| Gernandt, Hannes | University of Wuppertal, Germany |
| Grüne, Lars | University of Bayreuth, Germany |
| Günther, Michael | University of Wuppertal, Germany |
| Hinsen, Dorothea | TU Berlin, Germany |
| Itani, Mohammad | TU Hamburg, Germany |
| Karabash, Illia | University of Bonn, Germany |
| Karsai, Attila | TU Berlin, Germany |
| Liljegren-Sailer, Björn | RICAM and MathConsult Linz, Austria |
| Lohmayer, Markus | FAU Erlangen-Nürnberg, Germany |
| Maschke, Bernhard | Université Claude Bernard Lyon 1, France |
| Massai, Leonardo | EPFL, Switzerland |
| Morandin, Riccardo | TU Berlin, Germany |
| Müller, Matthias | Leibniz University Hannover, Germany |
| Nazari Monfared, Morteza | University of Pavia, Italy |
| Preuster, Till | Technische Universität Ilmenau, Germany |
| Püttschneider Jens | TU Dortmund, Germany |
| Saccani, Danilo | EPFL, Switzerland |
| Schießl, Jonas | University of Bayreuth, Germany |
| Schiller, Julian | Leibniz University Hannover, Germany |
| Sibeijn, Max | Delft University of Technology, The Netherlands |
| Singh, Vaibhav Kumar | University of Groningen, The Netherlands |
| Stykel, Tatjana | University of Augsburg, Germany |
| Totzeck, Claudia | University of Wuppertal, Germany |
| Unger, Benjamin | University of Stuttgart, Germany |
| Voigt, Matthias | UniDistance Suisse, Switzerland |
| Woytylak, Michał | Jagiellonian University, Kraków, Poland |
| Zakwan, Muhammad | EPFL, Switzerland |