Workshop
"Trends on Dissipativity in Systems and Control"

May 23–25, 2022 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 (but is not limited to):

- 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 Dortmund, Germany),
- Benjamin Unger (U Stuttgart, Germany),
- Matthias Voigt (UniDistance Suisse, Brig, Switzerland).

Further local support is provided by Milène Fauquex, Fabienne Ruffiner, 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 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),
- **Restaurant and Bar Lötschberg**, Bahnhofstrasse 8, 3904 Naters (1km from the campus).

2.3 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.

3 Daily Program

3.1 Monday, May 23, 2022

08:55	*Opening (Matthias Voigt)*
09:00	**Arjan van der Schaft** Port-Hamiltonian Systems and Energy Conversion
10:00	*Coffee Break*
10:30	**Ningbo Li** A Port-Hamiltonian Framework for Displacement-Based and Rigid Formation Tracking
11:00	**Catalin Arghir** A Feedback Passivation Framework for Control of Multi-Converter Power Systems
11:30	**Bernhard Maschke** Port Maps for Irreversible Interface Relations
12:00	*Lunch Break*
14:00	**Andrea Iannelli** Data-Driven Prediction and Control Through the Lens of System Identification
15:00	**Paul Schwerdtner** Optimization Based Control, Reduction, and Identification of Port-Hamiltonian Systems
15:30	**Tim Moser** Model Reduction of Port-Hamiltonian Descriptor Systems in MATLAB
16:00	*Coffee Break*
16:30	**Sara Grundel** Model Order Reduction of Structured Gas Networks
17:30	**Raffaele D'Ambrosio** Numerics for Mean-Square Dissipative Stochastic Differential Equations
19:00	*Conference Dinner*

Conference Dinner: The conference dinner will take place at *Restaurant and Bar Lötschberg, Bahnhofstrasse 8, 3904 Naters*, approximately 1km away from the conference site. The following menu has been prepared for us:

Mixed antipasti plate and Italian specialties
***
Cordon bleu (variant 1)
or
Veggi burger (variant 2)
or
Pasta/Lasagne al forno (variant 3)
***
Tiramisu

Variant 1 will cost approx. 40 CHF and variants 2 and 3 approx. 30 CHF per person without drinks. We would also like to ask you to pay dinner by yourself.

3.2 Tuesday, May 24, 2022

09:00	**Giancarlo Ferrari-Trecate** Hamiltonian Systems Meet Deep Networks
10:00	*Coffee Break*
10:30	**Carla Galimberti** A Compositional Port-Hamiltonian Approach of Distributed Neural Network Control with Stability Guarantees
11:00	**Luca Furieri** Neural System Level Synthesis: Learning over All Stabilizing Policies for Nonlinear Systems
11:30	**Stefan Volkwein** Data-driven Modeling and Control of Complex Dynamical Systems
12:00	*Lunch & Hike*
19:30	*Apéro & Poster Session* **Christian Jäkle, Lena Reichle** Modelling and Simulation of District Heating Networks **Jonas Kirchhoff** Relative Genericity for Linear Port-Hamiltonian Systems **Jonas Nicodemus** Identification of Passive Linear Time-Invariant Systems from Time Domain Data **Liang Xu** Neural Energy Casimir Control for Port-Hamiltonian Systems **Muhammad Zakwan** On Robust Classification using Contractive Hamiltonian Neural ODEs

Lunch & Hike: Please organize lunch by yourself. For the hike we will meet in front of the train station of Brig at 13:15. Thereafter, we will take the train to Hohtenn at 13:34 which will arrive at 13:53. We will then hike along the "Lötschberger Südrampe" (9.4km) to Ausserberg. On the way, there is the possibility to have a short stop at the restaurant "Bärgbeizi Rarner Chumma", but please take some water and food with you. It is also advised to wear appropriate clothes, especially sturdy shoes. There are trains back at 18:06 and 19:06 arriving in Brig at 18:20 and 19:20, respectively.
Apéro & Poster Session: The apéro will be combined with the poster session. There will be light food and free drinks including wine and beer.

3.3 Wednesday, May 25, 2022

09:00	**Manuel Schaller** Optimal Control and Dissipativity
10:00	**Lars Grüne** Strict Dissipativity for Multiobjective Optimal Control via Weighted Sums
10:30	**Majid Darehmiraki** Analysis of Some First Order Optimization Algorithms by Dissipativity Theory
11:00	*Coffee Break*
11:30	**Birgit Jacob** On Solvability of Dissipative Partial Differential-Algebraic Equations
12:30	**Benjamin Unger** Towards Port-Hamiltonian Systems with Time-Delays
13:00	*Closing (Matthias Voigt)*

4 Abstracts

Port-Hamiltonian Systems and Energy Conversion

Arjan van der Schaft (University of Groningen, the Netherlands)

Port-Hamiltonian systems modeling for analysis, simulation and control, is based on viewing the system as the power-conserving network interconnection of basic components. These components represent ideal physical behavior of energy storage, energy dissipation and energy routing; see e.g. [5, 1, 2]. Compared to general linear or nonlinear systems modeling port-Hamiltonian modeling makes explicit the underlying physical structure, including energy balance and other conservation laws. Furthermore, it is inherently compositional in the sense that power-conserving interconnection of port-Hamiltonian systems will result in another port-Hamiltonian system, of larger complexity.

In this talk we will utilize the port-Hamiltonian formulation in order to address a general energy conversion problem for multiphysics systems; see [3, 4] for further details. This problem can be described as follows. Consider a physical system with two power ports, e.g., an electrical port, with voltage inputs and current outputs, and a mechanical port, with force inputs and velocity outputs. The question is how, and to what extent, one can convert electrical energy supplied at the electrical port, into mechanical energy delivered to the environment at the mechanical port. An obvious example is the functioning of an electro-motor (or conversely, by swapping the two ports, the operation of a generator converting mechanical into electrical energy). Consider thereto the port-Hamiltonian formulation with two power ports, denoted as port 1 and port 2. Suppose that the state vector x of the port-Hamiltonian system can be split into two parts x_1 and x_2 corresponding to the two power ports 1 and 2, in such a way that the inputs of port 1 fully actuate the state sub-vector x_1, and moreover the interconnection and dissipation matrices are block-diagonal. For port-Hamiltonian systems with such a structure, but otherwise completely general, it turns out that when applying the input to port 1 in such a way that x_1 is kept constant, then the system at port 2 is *cyclo-passive*, and hence no energy can be extracted from port 2 in a repeatable manner. Furthermore, the same result holds if the input at port 1 is such that the output at port 1 is kept at a constant value. Hence in both cases no positive energy conversion from port 1 to port 2 can be achieved. On the other hand, by *switching* between two different constant values of the outputs at port 1, interlaced with trajectories for two different constant values of the state sub-vector x_1, energy conversion from port 1 to 2 *can* be achieved. This directly generalizes the situation considered in thermodynamics, where the design of a heat engine is aimed at converting thermal energy into mechanical energy (work). In fact, by the Second Law of thermodynamics no positive mechanical work is possible by either keeping the temperature (the output at port 1) equal to a single constant value, or along adiabatic curves (where the entropy is kept constant). But mechanical work *is* produced by the classical Carnot cycle, with the same Carnot efficiency. By means of a number of examples from different physical domains it will be shown that quite a few multiphysics systems satisfies these structural conditions. Thus these results leverage this fundamental engineering insight from thermodynamics to a large class of port-Hamiltonian systems, and show that thermodynamic systems are not so special in this regard. Finally, we will make some comments about port-Hamiltonian systems where the interconnection matrix is *not* block-diagonal, and thus there is direct topological connection between port 1 and 2. In this case the situation for energy conversion turns out to be fundamentally different.

[1] A.J. van der Schaft, *L_2-Gain and Passivity Techniques in Nonlinear Control*, 3rd Edition 2017, Springer International, Cham, Switzerland.

[2] A.J. van der Schaft, D. Jeltsema, *Port-Hamiltonian Systems Theory: An Introductory Overview*, Foundations and Trends in Systems and Control, vol. 1, no. 2/3, 173–378, 2014.

[3] A.J. van der Schaft, D. Jeltsema, "Limits to Energy Conversion," *IEEE Trans. Aut. Contr.*, 67(1), 532-538, 2021.

[4] A.J. van der Schaft, D. Jeltsema, "On Energy Conversion in Port-Hamiltonian Systems", Conf. Decision and Control, Austin, TX, USA, 2021.

[5] A.J. van der Schaft, B.M. Maschke, "The Hamiltonian Formulation of Energy Conserving Physical Systems with External Ports", *Archiv für Elektronik und Übertragungstechnik, 49*, 362–371, 1995.

A Port-Hamiltonian Framework for Displacement-Based and Rigid Formation Tracking

Ningbo Li (University of Groningen, the Netherlands)

Jacquelien Scherpen (University of Groningen, the Netherlands)
Arjan van der Schaft (University of Groningen, the Netherlands)
Zhiyong Sun (Eindhoven University of Technology, the Netherlands)

In [1], the notion of passivity is used for group coordination. The control objective is to steer the differences of output variables of neighboring agents to a prescribed compact set. By extending this idea to formation control, this work proposes a passivity approach in port-Hamiltonian (pH) form for formation stabilization and velocity tracking. The control law consists of two parts, where the internal feedback is to track the velocity and the external feedback is to achieve formation stabilization. A necessary condition to achieve convergence to the target set is the linear independence of the columns of the incidence matrix of an underlying interaction graph. However, for formation control, this condition is often not satisfied, for example in the displacement-based formation of cyclic graphs. Also in the case of rigid formations, such as distance-based and bearing-based formations, the underlying graph usually contains cycles. The objective of this work is to extend the passivity approach to displacement-based formation and rigid formation in case of cyclic graphs.

We consider a group of N agents coupled by an underlying graph with M edges, while each agent is modeled in pH form as a single point mass in $\mathbb{R}^d$.

$$\begin{pmatrix} \dot{q} \\ \dot{p} \end{pmatrix} = \begin{pmatrix} 0 & I_{Nd} \\ -I_{Nd} & -D^r \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial q}(p) \\ \frac{\partial H}{\partial p}(p) \end{pmatrix} + \begin{pmatrix} 0 \\ I_{Nd} \end{pmatrix} u$$
$$y = \frac{\partial H}{\partial p}(p)$$

where $q \in \mathbb{R}^{Nd}$, $p \in \mathbb{R}^{Nd}$, $u \in \mathbb{R}^{Nd}$, and $y \in \mathbb{R}^{Nd}$ is the position, momentum, input, and output, respectively. $D^r \in \mathbb{R}^{Nd \times Nd}$ is a positive semi-definite dissipation matrix. The Hamiltonian consists of the kinetic energy associated with the movement of the mass and takes the following form $H = \frac{1}{2}\sum_{i=1}^{N} p_i^T M_i^{-1} p_i$, where $M_i = m_i I_d$.

The coordination objective for the group behavior consists of two parts. One is that the velocity of each agent converges to a prescribed common value, i.e.,

$$\lim_{t\to\infty} |\dot{q}_i(t) - v^*(t)| = 0.$$

The other is that the position difference variables associated with the edges

$$z = (B^T \otimes I_d)q$$

converge to a prescribed compact set $\Xi \subset \mathbb{R}^{M \times d}$, where $\Xi = \{z_1^*, z_2^*, ..., z_M^*\}$ and $z_j^*, j = 1, 2, ..., M$ is the prescribed difference variable associated with edges j. B is the incidence matrix.

In this work, a passivity approach in pH form for formation stabilization and velocity tracking is proposed. For displacement-based formation, by choosing the proper Hamiltonian function for formation stabilization, the proposed approach can be applicable for not only the acyclic graphs but also the cyclic graphs. For distance-based formation, by establishing the relationship between infinitesimal rigidity and time derivative of the Hamiltonian, the local convergence of the proposed formation system is guaranteed. For bearing-based formation, the almost global convergence can be obtained since the infinitesimal bearing rigidity is sufficient to global bearing rigidity.

[1] M. Arcak. Passivity as a design tool for group coordination. *IEEE Transactions on Automatic Control*, 52(8):1380–1390, 2007.

A Feedback Passivation Framework for Control of Multi-Converter Power Systems

Catalin Arghir (RUAG Space, Switzerland)

This work, first introduced in [1, 2], investigates nonlinear control design for two classes of power conversion systems in electrical networks: the synchronous generator and the three-phase DC/AC converter. Starting from first-principles, we adopt a geometric approach and arrive at the problem of stabilizing a motion corresponding to the optimal network flow in an electrical circuit. A model-matching procedure is proposed to induce convenient gradient dynamics for the radial as for the angular coordinates. The rotor angle and the logarithm of the excitation current become generalized coordinates of choice for a Hamiltonian system. We then explore ways of shaping the energy in the aim of tracking given active and reactive power set points. This approach allows us to systematically study the steady-state behavior, recover engineering intuition and implement decentralized controllers. In addition, an experimental evaluation is pursued.

[1] C. Arghir. Transverse feedback passivation in control of multi-machine and multi-converter power networks. *ETH Zurich, ISBN 978-3-907234-03-7, June 2020.*

[2] C. Arghir. and F. Dörfler. Energy-based stabilization of network flows in multi-machine power systems. *The 23rd International Symposium on Mathematical Theory of Networks and Systems (MTNS 2018), Hong Kong, July 16-20, 2018.*

Port Maps for Irreversible Interface Relations

Bernhard Maschke (Univ Lyon, Université Claude Bernard Lyon 1, CNRS, LAGEPP UMR 5007, France)

Arjan van der Schaft (Bernoulli Institute for Math., Computer Sci. and AI, University of Groningen, the Netherlands)

Port Hamiltonian Systems are the extension of Hamiltonian systems (defined on the state space chosen, for simplicity, to be $\mathbb{R}^n$) to *open* systems which exchange energy with their environment. This extension is realized by adding an input map (linear in the input $u(t)$) and the adjoint map defining the power-conjugated output $y(t)$, defined the control vector field $g(x)$ leading to the definition of Port Hamiltonian Systems [1]

$$\begin{pmatrix} \frac{dx}{dt} \\ -y \end{pmatrix} = \begin{pmatrix} J(x) & g(x) \\ -g(x)^\top & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial x} \\ u \end{pmatrix} \tag{4.1}$$

These systems have been proven to be closed by power continuous interconnection which has led to passivity-based control method [2].

In this talk, we shall consider Irreversible Port Hamiltonian Systems [4, 3, 5] which are generalizations of Port Hamiltonian Systems where the drift term is defined by a quasi-Poisson structure which allows to account for both the energy conservation and the irreversible entropy creation associated with dissipative phenomena. We shall show that, accounting for a dissipative phenomenon at the interface of the system with its environment leads to the following natural extension

$$\frac{dx}{dt} = \gamma\left(x, \tfrac{\partial H}{\partial x}\right)\{S, H\}_J\, J\frac{\partial H}{\partial x}(x) + \gamma_{\mathrm{port}}\left(x, \tfrac{\partial H}{\partial x}, u\right)\left[\left(g^\top \frac{\partial S}{\partial x}\right)^\top u - \tau^\top \left(g^\top \frac{\partial H}{\partial x}\right)\right] g\, u \quad (4.2)$$

$$y = \gamma_{\mathrm{port}}\left(x, \tfrac{\partial H}{\partial x}, u\right)\left[\left(g^\top \frac{\partial S}{\partial x}\right)^\top u - \tau^\top \left(g^\top \frac{\partial H}{\partial x}\right)\right] g^\top \frac{\partial H}{\partial x} \quad (4.3)$$

generated by the two (smooth) real functions called Hamiltonian function $H(x) \in C^\infty(\mathbb{R}^n)$ and entropy function $S(x) \in C^\infty(\mathbb{R}^n)$, $J \in \mathbb{R}^n \times \mathbb{R}^n$ which is constant and skew-symmetric matrix defining a Poisson bracket $\{S, H\}_J = \frac{\partial S}{\partial x}^\top(x)\, J\frac{\partial H}{\partial x}(x)$, γ and γ_{port} are strictly positive functions and the pair $u(t)$ and $\tau \in \mathbb{R}$define the input map.

The passivity-properties shall be discussed and different illustrating examples presented.

[1] B.M. Maschke and A.J. van der Schaft. Port-controlled Hamiltonian Systems: Modelling Origins and System-theoretic Properties. In M. FLIESS, editor, *Nonlinear Control Systems Design 1992*, IFAC Symposia Series, pages 359–365. Pergamon, Oxford, 1993.

[2] R. Ortega, A.J. van der Schaft, I. Mareels, and B. Maschke. Putting energy back in control. *IEEE Control Systems Magazine*, 21(2):18– 32, April 2001.

[3] H. Ramirez, B. Maschke, and D. Sbarbaro. Irreversible port-Hamiltonian systems: A general formulation of irreversible processes with application to the CSTR. *Chemical Engineering Science*, 89(0):223 – 234, 2013.

[4] H. Ramirez, B. Maschke, and D. Sbarbaro. Modelling and control of multi-energy systems: An irreversible Port-Hamiltonian approach. *European Journal of Control*, 19(6):513 – 520, 2013.

[5] H. Ramirez, Y. Le Gorrec, B. Maschke, and F. Couenne. On the passivity based control of irreversible processes: A Port-Hamiltonian approach. *Automatica*, 64:105 – 111, 2016.

Data-Driven Prediction and Control Through the Lens of System Identification

Andrea Iannelli (Automatic Control Lab, ETH Zürich, Switzerland)

The need to perform increasingly challenging tasks has been addressed in several application domains by a paradigm shift in the design of systems. For such complex systems, first-principles modelling is often not a viable solution to provide sufficiently accurate mathematical models which are useful to make reliable predictions and satisfactorily control them. On the other hand, an unprecedented amount of data is available from these systems. Therefore system identification, which traditionally studies the problem of building mathematical models of dynamical systems from experimental observations, seems an ideal candidate to tackle this problem. Unfortunately, traditional parametric approaches often fail to obtain a reliable model of the system. In fact, it can be questioned whether projecting the available data onto a predefined model class is really needed in the first place, instead of making predictions and taking actions directly from data. This has motivated recently extensive research in direct data-driven methods, boosted to a large extent by the celebrated Willems (or *Fundamental*) Lemma from behavioral system theory [1].

This talk will present our ongoing work on the Signal Matrix Model (SMM), an implicit non-parametric representation of linear dynamical systems consisting of matrices assembled directly from data. At a conceptual level, SMM seeks an extension of the Willems Lemma, which in the noise-free case guarantees that all and only finite trajectories of a linear system are in the range of matrices built with persistently exciting data, to the case where observations are noisy. The goal is to provide a statistically principled framework for simulation, signal denoising, and control which uses directly raw noisy data instead of requiring a parametric model of the system. The talk illustrates how we attempt to address this problem by taking a system identification viewpoint. First, it will be discussed how this behavioural system theory result can be cast in a Bayesian setting and used for prediction and control [2]. Then, two important aspects enabled by the stochastic formulation of the problem are discussed. One concerns data informativity, prompted by the observation that different persistently exciting inputs will lead, contrary to the noise-free setting, to different data-based predictors [3]. To this aim, a Bayesian design of experiment approach using information theoretic criteria in conjunction with SMM [4] is discussed. The second is the definition of confidence regions of the stochastic predictors starting from the prediction error distribution, whereby statistical guarantees of prediction accuracy can be obtained [5]. A discussion on the current limitations of the framework, future extensions, and foreseeable challenges will conclude the talk.

[1] J. C. Willems, P. Rapisarda, I. Markovsky, and B. L. M. De Moor, "A note on persistency of excitation," *Systems & Control Letters*, vol. 54, no. 4, pp. 325–329, 2005.

[2] M. Yin, A. Iannelli, R. S. Smith. Maximum Likelihood Estimation in Data-Driven Modeling and Control. *IEEE Transactions on Automatic Control*, 2021.

[3] A. Iannelli, M. Yin, R. S. Smith. Experiment design for impulse response identification with signal matrix models. *IFAC Symposium on System Identification*, 2021.

[4] A. Iannelli, M. Yin, R. S. Smith. Design of input for data-driven simulation with Hankel and Page matrices. *IEEE Conference on Decision and Control*, 2021.

[5] M. Yin, A. Iannelli, R. S. Smith. Data-driven prediction with stochastic data: confidence regions and minimum mean-squared error estimates. *European Control Conference*, 2022.

Optimization Based Control, Reduction, and Identification of Port-Hamiltonian Systems

Paul Schwerdtner (TU Berlin, Germany)

Tim Moser (TU München, Germany)
Matthias Voigt (Fernuni Schweiz, Switzerland)

In the first part of the talk, we present our algorithm *SOBMOR* for structure-preserving model order reduction of linear constant coefficient port-Hamiltonian (pH) systems, developed in [1, 2]. SOBMOR is a framework for model order reduction (MOR) of pH systems, i. e. it determines approximations of pH models with a large state dimension (model order) with pH reduced order models (ROM) that a small state dimension. In contrast to other well-established MOR techniques, SOBMOR is not based on projection but determines the ROM by directly optimizing the ROM parameters (i. e. the elements of the system matrices). The objective functional penalizes the difference between the FOM and ROM transfer function at an adaptively chosen set of frequency samples. Our past investigations [1, 2] show the effectiveness of SOBMOR for structure preserving MOR.

In the second part, we show how this optimization-based approach can be used to solve a broader range of problems. These include (i) the MOR of pH systems based on differential-algebraic equations, (ii) the identification of pH systems from noisy data (see [3] for a preliminary study), and (iii) the $\mathcal{H}_\infty$ control of pH systems.

[1] P. Schwerdtner and M. Voigt SOBMOR: Structured Optimization Based Model Order Reduction March 2022. Revision submitted for publication, preliminary version also available as Preprint arXiv:2011.07567

[2] P. Schwerdtner and M. Voigt. Adaptive sampling for structure-preserving model order reduction of port-Hamiltonian systems. *IFAC-PapersOnLine*, 54(19):143–148, 2021. 7th IFAC Workshop on Lagrangian and Hamiltonian Methods for Nonlinear Control, Berlin, Germany, 2021.

[3] P. Schwerdtner. Port-Hamiltonian System Identification from Noisy Frequency Response Data Preliminary version available at `https://arxiv.org/pdf/2106.11355.pdf`

Model Reduction of Port-Hamiltonian Descriptor Systems in MATLAB

Tim Moser (Technical University of Munich, Germany)

Volker Mehrmann (TU Berlin, Germany)
Paul Schwerdtner (TU Berlin, Germany)
Matthias Voigt (UniDistance Suisse, Switzerland)

We present a novel optimization-based framework for the structure-preserving model reduction of port-Hamiltonian differential-algebraic systems (pH-DAEs). These systems naturally emerge in the modeling of complex systems, as they allow to include preservation laws such as mass balances in chemical processes or network laws such as Kirchhoff's laws in electrical circuits into the model. The reduction of large-scale pH-DAEs is dominated by two types of constraints. On the one hand, it is desired to retain the port-Hamiltonian structure in order to preserve inherent properties such as passivity. On the other hand, the reduced model has to respect the algebraic equations and their impact on the input-to-output behavior. As shown in previous work [1, 2], these constraints may be challenging to incorporate in the traditional Petrov-Galerkin framework for model reduction. We therefore propose an optimization-based approach which is based on a novel parameterization that allows to represent any linear time-invariant pH-DAE with a minimal set of parameters and is therefore well-suited for model reduction. If we use this parameterization for the reduced model, we may optimize its parameter set in an $\mathcal{H}_2$-inspired way by exploiting the computationally efficient pole-residue formulation of the $\mathcal{H}_2$ error proposed in [3]. Consequently, both types of constraints are respected and the method is entirely based on transfer function evaluations of the large-scale model and therefore independent of its system matrix structure. Our methods are part of a new toolbox for the modeling, interconnection and reduction of pH-DAEs in MATLAB which will be open-source and provides intuitive interfaces for users with different experience levels.

[1] C. A. Beattie, S. Gugercin, V. Mehrmann. Structure-preserving interpolatory model reduction for port-Hamiltonian differential-algebraic systems. In C. Beattie, P. Benner, M. Embree, S. Gugercin, S. Lefteriu, editors, *Realization and Model Reduction of Dynamical Systems: A Festschrift in Honor of the 70th Birthday of Thanos Antoulas*, Springer, Cham, 2022.

[2] S.-A. Hauschild, N. Marheineke, V. Mehrmann, Model reduction techniques for linear constant coefficient port-Hamiltonian differential-algebraic systems. *Control and Cybernetics*, 48(1):125–152, 2019.

[3] L. Meier and D. Luenberger. Approximation of linear constant systems. *IEEE Transactions on Automatic Control*, 12(5):585–588, 1967.

Model Order Reduction of Structured Gas Networks

Sara Grundel (MPI Magdeburg, Germany)

Modeling and simulation of the transient gas network leads to several numerical challenges. Using the right modeling framework can make a large impact in reducing the overall simulation time in particular for large network systems. It can in particular prevent tiny time steps in a simulation and can also make model order reduction frameworks more stable.

From an application driven point of you an interesting questions today is what happens if we insert hydrogen at certain nodes within a large gas pipeline network. What quality of the gas at the end user can a pipeline operator guarantee? This means in particular how can the composition of the gas over time and over the network be computed? We will discuss different modeling frameworks as well as solvers for the classical problem as well as the more complex multi-component flow. We will particular dive a bit into a variety of model order reduction methods [1, 2] and discuss the importance of the concept of dissipativity for certain applications.

[1] S. Grundel, and M. Herty. Model-order reduction for hyperbolic relaxation systems. *International Journal of Nonlinear Sciences and Numerical Simulation*, 2022.

[2] C. Himpe, S. Grundel, and P. Benner. Model order reduction for gas and energy networks. *Journal of Mathematics in Industry*, 11(1): 1-46, 2021

Numerics for Mean-Square Dissipative Stochastic Differential Equations

Raffaele D'Ambrosio (University of L'Aquila, Italy)

Evelyn Buckwar (Johannes Kepler University of Linz, Austria)
Stefano Di Giovacchino (University of L'Aquila, Italy)

We address our investigation to the preservation of mean-square contractivity along discretized dynamics given by the stochastic multistep and Runge-Kutta methods applied to mean-square dissipative stochastic differential equations [1, 2, 3, 4]. The interest in these problems is wide and covers several fields, such as finance and economics, neural networks, population dynamics, systems synchronization, stochastic differential equations with jumps, dynamical systems, delay ordinary (and stochastic) differential equations (see [2, 5] and references therein). Regarding stochastic multistep methods, these properties are translated in terms of suitable restrictions on the stepsize [1, 2]. Concerning stochastic Runge-Kutta methods, we show how this conservation property is inherited along the solutions generated by the stochastic perturbation of algebraically stable deterministic Runge-Kutta methods [3]. Suitable numerical experiments are provided to confirm the sharpness of the theoretical results.

[1] E. Buckwar, R. D'Ambrosio, Exponential mean-square stability properties of stochastic linear multistep methods, Advances in Computational Mathematics 47, article number 55 (2021).

[2] R. D'Ambrosio, S. Di Giovacchino, *Mean-square contractivity of stochastic θ-methods*, Communications in Nonlinear Science and Numerical Simulations, 96, 105671 (2021).

[3] R. D'Ambrosio, S. Di Giovacchino, *Nonlinear stability issues for stochastic Runge-Kutta methods*, Communications in Nonlinear Science and Numerical Simulations, 94, 105549 (2021).

[4] D. Higham, P. Kloeden, *Numerical methods for nonlinear stochastic differential equations with jumps*, Numerische Mathematik, 101 (2005), pp. 101–119.

[5] M. Hutzenthaler, A. Jentzen, Numerical approximations of stochastic differential equations with non-globally Lipschitz continuous coefficients, Memoirs of the American Mathematical Society 236(1112), doi: 10.1090/memo/1112 (2015).

Hamiltonian Systems Meet Deep Networks

Giancarlo Ferrari-Trecate (EPFL, Switzerland)

Deep neural networks have achieved an amazing success in various fields like computer vision, speech recognition and natural language processing. Moreover, today, they are at the heart of many machine learning algorithms. Yet, their training can be difficult due to occurrence of vanishing and exploding gradients during weight optimization through backpropagation. To address this problem, I will introduce a general class of Hamiltonian Deep Neural Networks (H-DNNs) that stem from the discretization of continuous-time Hamiltonian systems and include several existing architectures based on ordinary differential equations. The main result is that a broad set of H-DNNs ensures non-vanishing gradients by design for an arbitrary network depth. We also provide an upper bound to the magnitude of sensitivity matrices, and show that exploding gradients can be controlled through regularization. The good performance of H-DNNs will be demonstrated on benchmark classification problems, including image classification with the MNIST and CIFAR 10 datasets.

A Compositional Port-Hamiltonian Approach of Distributed Neural Network Control with Stability Guarantees

Clara Lucía Galimberti (EPFL, Switzerland)

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

[1]Large-scale cyber-physical systems require that control policies are *distributed*, that is, that they only rely on local real-time measurements and communication with neighboring agents. Optimal Distributed Control (ODC) problems are, however, highly intractable even in seemingly simple cases. Recent work [1] has thus proposed training Neural Network (NN) distributed controllers. A main challenge of NN controllers is that they are not *dependable* during and after training, that is, the closed-loop system may be unstable, and the training may fail due to vanishing gradients. In this paper, we address these issues for networks of nonlinear port-Hamiltonian (pH) systems, whose modeling power ranges from energy systems to non-holonomic vehicles and chemical reactions. Specifically, we embrace the compositional properties of pH systems to characterize deep Hamiltonian control policies with *built-in* closed-loop stability guarantees — irrespective of the interconnection topology and the chosen NN parameters. Furthermore, our setup enables leveraging recent results on Hamiltonian Deep Neural Networks (H-DNNs) [2] to prevent the phenomenon of vanishing gradients by design.

We validate our results by considering a fleet of 12 mobile robots that need to achieve a formation on the xy-plane within a given time $T \in \mathbb{R}$ 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 loss function. Figure 4.1 (left) presents the obtained collision free trajectories after training a distributed H-DNN controller. particular,

In Figure 4.1 (right), we plot the norms of the backward sensitivity matrices (BSMs) — which is closely related to the gradient of the loss function with respect to the parameters. The plot confirms that gradients never tend to vanish, despite a high number of layers in the trained architecture.

[1]The paper and the code for numerical examples are available at https://github.com/DecodEPFL/DeepDisCoPH.

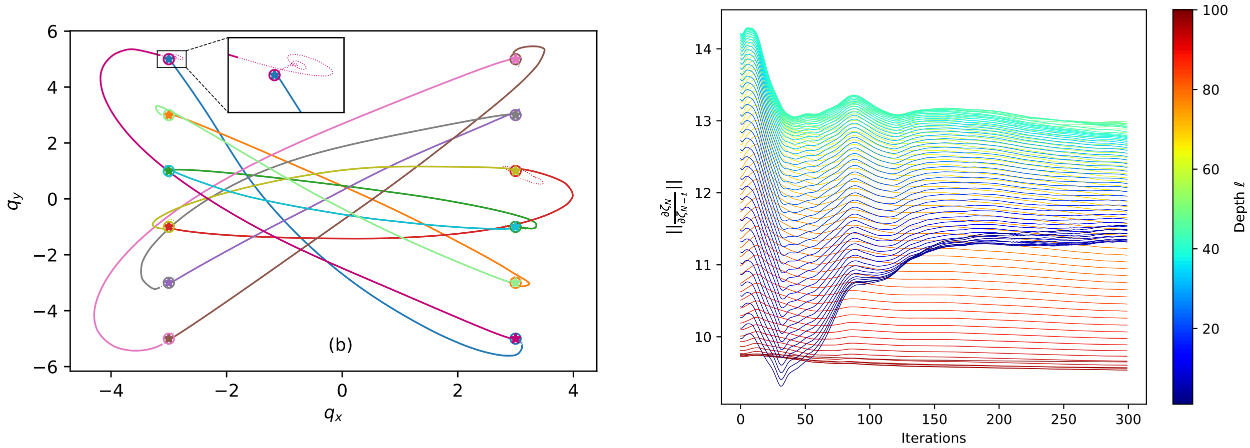

Figure 4.1: (Left) Trajectories of the robots in the xy-plane after training a distributed H-DNN controller. Dotted lines indicate the trajectories for $t > T$, where T is the training horizon. Target positions indicated with $\circ$. Initial positions indicated with $\star$. (Right) Norms of the BSMs.

[1] F. Gama and S. Sojoudi. Graph neural networks for distributed linear-quadratic control. *Learning for Dynamics and Control*, pages 111–124. PMLR, 2021.

[2] C.L. Galimberti, L. Furieri, L. Xu and G. Ferrari-Trecate. Hamiltonian Deep Neural Networks Guaranteeing Non-vanishing Gradients by Design. *arXiv preprint arXiv:2105.13205*, 2021.

Neural System Level Synthesis: Learning over All Stabilizing Policies for Nonlinear Systems

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[2]We address the problem of designing stabilizing control policies for nonlinear systems in discrete-time, while minimizing an arbitrary cost function. When the system is linear and the cost is convex, the System Level Synthesis (SLS) approach [1] offers an exact solution based on convex programming. Beyond this case, a globally optimal solution cannot be found in a tractable way, in general. Our key finding is that the intractable constraints of nonlinear SLS [2] need not be imposed during optimization, if a stabilizing base control policy is known, and if this base control policy defines itself a stable map from its inputs to its outputs. In this case, *all and only* the other stabilizing policies are parametrized in terms of a freely chosen stable SLS operator. Based on this result, we propose a Neural SLS approach guaranteeing closed-loop stability during and after parameter optimization, without requiring any constraints to be satisfied. We exploit recent Deep Neural Network (DNN) models based on Recurrent Equilibrium Networks (RENs) [3] to learn over a rich class of nonlinear stable operators, and demonstrate the effectiveness of the proposed approach in numerical examples.

Figure 4.2 (left) illustrates the proposed parametrization of *all and only* stabilizing controllers. We validate our results in a task involving two agents that need to pass through a valley while avoiding collisions and optimally reaching a fixed target point. Figure 4.2 (right) shows the closed-loop trajectories after training when starting from initial conditions marked with $\circ$.

[2]The report and the code for numerical examples are available at https://github.com/DecodEPFL/neurSLS.

The proposed system-level perspective may open up several venues for future research, including extension to output-feedback and applications to constrained, distributed and data-driven nonlinear control.

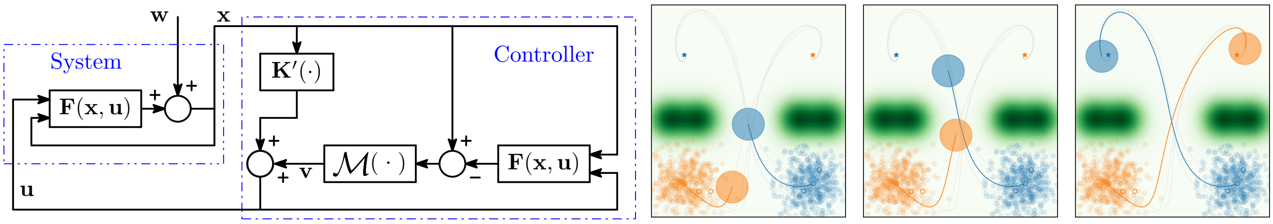

Figure 4.2: (Left) Proposed parametrization of all stabilizing controllers in terms of one freely chosen non-linear ℓ_p-stable operator $\mathcal{M}$. (Right) Closed-loop trajectories after the training of Neural SLS. Colored balls (and their radius) represent the agents (and their size for collision avoidance).

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Data-Driven Modeling and Control of Complex Dynamical Systems

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In this talk control strategies are discussed for dynamical systems; cf. [1]. By data-driven strategies we derive surrogate models for the complex dynamics. The proposed strategies are illustrated by numerical experiments for mathematical model of erythropoiesis for anemia [2, 3] and for heat-convection phenomena [4]. The data-driven modeling extended dynamic mode decomposition (EDMD) and empirical grammians are utilized. This allows for efficient and reliable strategies based on a combination of EDMD and model predictive control, which produces results comparable with the one obtained in [5] for the original model. Moreover, multiobjective problems are considered as well and numerical tests show that advantages of empirical gramian approach compared to standard POD surrogate modeling.

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Modelling and Simulation of District Heating Networks

Christian Jäkle (University of Konstanz, Germany)
Lena Reichle (University of Konstanz, Germany)

Stefan Volkwein (University of Konstanz, Germany)

In the present poster a detailed mathematical model is derived for district heating networks. After semidiscretization of the convective heat equation and introducing coupling conditions at the nodes of the network one gets a high-dimensional system of differential-algebraic equations (DAEs). Neglecting temporal changes of the water velocity in the pipes, the numerical solutions do not change significantly and the DAEs have index one. Numerical experiments illustrate that the model describes the real situation very well.

Based on the obtained mathematical model optimal control problems are considered. The still ongoing interest is on one hand the development of efficient nonlinear optimization methods to get optimal solutions for the network. On the other hand port-Hamiltonian formulations allow for the applying control theoretic strategies.

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Relative Genericity for Linear Port-Hamiltonian Systems

Jonas Kirchhoff (Technische Universität Ilmenau, Germany)

We use the concept of relative genericity introduced in [3] to show that linear port-Hamiltonian descriptor systems of the form

$$\tfrac{\mathrm{d}}{\mathrm{d}t}Ex = (J-R)Qx + Bu \tag{4.4}$$

with $E, J, R, Q \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$ so that $J = J^\top$, $E^\top Q = Q^\top E \geq 0$ are generically "controllable". "Controllable" stands for the five controllability concepts of freely initializable (controllable at infinity), impulse controllable, controllable in the behavioural sense, strongly controllable and completely controllable systems, whose algebraic characterizations can be found in the survey article [1] by Berger and Reis. Analogously to [2], where genericity of controllability for general linear differential algebraic systems was proven, we show that the rank of the (polynomial) block matrices appearing in the aforementioned algebraic criteria is full on a relative generic subset of the reference set

$$\left\{(E, J, R, Q, B) \,\middle|\, E, J, R, Q \in \mathbb{R}^{n\times n}, B \in \mathbb{R}^{n\times m}, J = J^\top, E^\top Q = Q^\top E \geq 0\right\}.$$

We then use the fact that the finite intersection of relative generic subsets of a fixed reference set is also relative generic in said reference set to prove that controllability is indeed a generic property of linear port-Hamiltonian systems of the form (4.4). Therefore, we conclude analogously to [3] that a system (4.4) given by random, but continuously distributed matrices is almost surely controllable.

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Identification of Passive Linear Time-Invariant Systems from Time Domain Data

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We present a novel physics-informed system identification method to construct a passive linear time-invariant system. In more detail, for a given quadratic energy functional, measurements of the input, state, and output of a system in the time domain, we find a realization that approximates the data well while guaranteeing that the energy functional satisfies a dissipation inequality. One of the main advantages of requiring the learned model to satisfy a dissipation inequality is that whenever the model is coupled with another passive model via a powerconserving or dissipative interconnection, then the coupled model is also passive. To this end, we use the framework of port-Hamiltonian (pH) systems [1] and modify the dynamic mode decomposition (DMD) [2] to be feasible for continuous-time pH systems. We propose an iterative numerical method to solve the corresponding least-squares minimization problem and construct an effective initialization by studying the least-squares problem in a weighted norm, for which we present the analytical minimum-norm solution. The efficiency of the proposed method is demonstrated with several numerical examples.

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Neural Energy Casimir Control for Port-Hamiltonian Systems

Liang Xu (Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland)

Muhammad Zakwan (Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland)
Giancarlo Ferrari-Trecate (Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland)

The energy Casimir method is an effective controller design approach to stabilize port-Hamiltonian systems at a desired equilibrium. However, its application relies on the availability of suitable Casimir and Lyapunov functions, whose computation are generally intractable. In this paper, we propose a neural network-based framework to learn these functions. We show how to achieve equilibrium assignment by adding suitable regularization terms in the training cost. We also propose a parameterization of Casimir functions for reducing the training complexity. Moreover, the distance between the equilibrium of the learned Lyapunov function and the desired equilibrium is analyzed, which indicates that for small suboptimality gaps, the distance decreases linearly with respect to the training loss. Our methods are backed up by simulations on a pendulum system.

The full-text is accessible from [1].

[1] L. Xu, M. Zakwan, and G. Ferrari-Trecate. Neural Energy Casimir Control for Port-Hamiltonian Systems. *arXiv pre-print*, 2022, https://arxiv.org/abs/2112.03339

On Robust Classification using Contractive Hamiltonian Neural ODEs

Muhammad Zakwan (Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland)

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Deep neural networks can be fragile and sensitive to small input perturbations that might cause a significant change in the output. In this paper, we employ contraction theory to improve the robustness of neural ODEs (NODEs). A dynamical system is contractive if all solutions with different initial conditions converge to each other asymptotically. As a consequence, perturbations in initial conditions become less and less relevant over time. Since in NODEs, the input data corresponds to the initial condition of dynamical systems, we show contractivity can mitigate the effect of input perturbations. More precisely, inspired by NODEs with Hamiltonian dynamics, we propose a class of contractive Hamiltonian NODEs (CH-NODEs). By properly tuning a scalar parameter, CH-NODEs ensure contractivity by design and can be trained using standard backpropagation and gradient descent algorithms. Moreover, CH-NODEs enjoy built-in guarantees of non-exploding gradients, which ensures a well-posed training process. Finally, we demonstrate the robustness of CH-NODEs on the MNIST image classification problem with noisy test datasets.

Optimal Control and Dissipativity

Manuel Schaller (TU Ilmenau, Germany)

In this talk, we will discuss the role of dissipativity for the analysis of optimal control problems, its connection to the turnpike property, and its use for efficient numerical methods.

After introducing dissipativity concepts for optimal control of finite and infinite dimensional systems, we will inspect the intimate relation of dissipativity in optimal control with the turnpike property [1]. The latter constitutes a stability property of optimal control problems and states that optimal solutions reside close to particular points in state space for the majority of the time.

In the second part of the talk, we will focus on structure-exploiting optimal control of port-Hamiltonian systems. Here, for linear dissipative port-Hamiltonian systems, we will observe and prove a turnpike property with respect to a conservative subspace [2, 3], whereas for nonlinear irreversible systems we obtain a turnpike property towards the manifold of thermodynamical equilibria [4].

Last, we will inspect efficient numerical schemes emerging from dissipativity in optimal control. In this context, we showcase how the turnpike property and its inherent stability enables the design and analysis of efficient space-time discretization or domain decomposition methods [5].

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[2] M. Schaller, F. Philipp, T. Faulwasser, K. Worthmann and B. Maschke. Control of port-Hamiltonian systems with minimal energy supply. *European Journal of Control*, 62:33–40, 2021.

[3] T. Faulwasser, B. Maschke, F. Philipp, M. Schaller and K. Worthmann. Optimal control of port-Hamiltonian descriptor systems with minimal energy supply. To appear in *SIAM Journal on Control and Optimization*, 2022.

[4] B. Maschke, F. Philipp, M. Schaller, K. Worthmann and T. Faulwasser. Optimal control of thermodynamic port-Hamiltonian Systems. submitted, preprint:arXiv:2202.09086, 2022.

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Strict Dissipativity for Multiobjective Optimal Control Via Weighted Sums

Lars Grüne (University of Bayreuth, Germany)

Lisa Krügel (University of Bayreuth, Germany)
Matthias A. Müller (University of Hanover, Germany)

The weighted-sum approach is one of the simplest yet effective methods for solving multiobjective optimization problems [1]. Due to its simplicity, it carries over without any difficulties to optimal control and to model predictive control (MPC). Since multiple conflicting optimization objectives (such as speed, fuel consumption, and driving comfort in automotive applications or stability and high yield in chemical process control) are ubiquitous in real world problems in which MPC has been successfully applied, it is natural to study this situation [2, 5, 6, 7].

However, for MPC schemes to deliver approximately optimal closed-loop solutions, typically strict dissipativity of the underlying optimal control problem is needed [3]. Besides, strict dissipativity is also a useful property for determining the long-term behaviour of the optimal solutions [4]. This motivates to study strict dissipativity of optimal control problems.

In this talk we investigate whether an optimal control problem with a weighted-sum objective composed from various individual objectives is strictly dissipativity. Particularly, we investigate whether strict dissipativity for the individual objectives carries over to the weighted-sum objective.

Depending on the structure of the problem (linear-quadratic, convex, general nonlinear) different necessary, sufficient and also necessary and sufficient conditions are presented.

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Analysis of Some First Order Optimization Algorithms by Dissipativity Theory

Majid Darehmiraki (Behbahan Khatam Alanbia University of Technology, Khouzestan, Iran)

Due to the widespread use of first-order algorithms in machin learning, analysis and design of these algorithms is one of the hot topics in optimization. Because first-order algorithms can be very slow, even for problems with intermediate conditions. In this regard, accelerated types of first-order algorithms, such as the Polyac heavy ball algorithm [5] or the Nestor acceleration method, have been developed to accelerate convergence. Since iterative algorithms can also be interpreted as feedback dynamical systems, the tools in control theory can also be used to analyze these algorithms [2, 4]. Recently, Fazlyab et al. [1] analyzed these algorithms using integral quadratic constraints. Hu and Lessard also analyzed the accelerated Nestorov algorithm using dissipativity theory [3]. In this paper, we make a connection between quadratic integral inequalities and discretization attitudes using dissipativity theory [6], and then analyze some first-order algorithms. With the help of dissipation theory we can make Lyapunov function more efficiently just by solving a small semidefinite program [7].

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On Solvability of Dissipative Partial Differential-Algebraic Equations

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In this article we investigate the solvability of infinite-dimensional differential algebraic equations. Such equations often arise as partial differential-algebraic equations (PDAEs). A decomposition of the state-space that leads to an extension of the Hille-Yosida Theorem on Hilbert spaces for these equations is described. For dissipative partial differential equations the famous Lumer-Phillips generation theorem characterizes solvability and also boundedness of the associated semigroup. An extension of the Lumer-Phillips generation theorem to dissipative differential-algebraic equations is given. The results is illustrated by coupled systems and the Dzektser equation.

Towards Port-Hamiltonian Systems with Time-Delays

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Over the last two decades, the scope of port-Hamiltonian (pH) systems, cf. [3, 4], has been systematically increased to discrete-time systems, differential-algebraic equations, and partial differential equations. Nevertheless, a systematic pH model class for systems with internal time-delay of the form

$$\dot{z}(t) = A_0 z(t) + A_1 z(t-\tau) + Bu(t), \tag{4.5a}$$

$$y(t) = Cz(t), \tag{4.5b}$$

where $A_0, A_1 \in \mathbb{R}^{n\times n}$, $B, C^T \in \mathbb{R}^{n\times m}$ is not available. In the non-delayed case, which is obtained if either $\tau = 0$ or $A_1 = 0$ in (4.5). For systems of the form (4.5) it is well-known that they can be recast in the pH framework if and only if (4.5) is passive [1]. Moreover, any system is passive if and only if the associated Kalman-Yakubovich-Popov (KYP) inequality can be solved. Any solution of the KYP can then be used to construct an explicit pH representation. We follow this idea by recasting the time-delay system (4.5) as an infinite-dimensional operator equation without delay [2], for which we study special solutions of the corresponding operator KYP inequality. The pH formulation on the operator level is then recast as a time-delay equation, which forms the basis for our definition of a time-delay pH system.

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