DY 49: Focus Session: Computing with Dynamical Systems: New Perspectives on Reservoirs and Applications II – Applications and Quantum RC

Reservoir Computing uses the dynamic response of driven dynamical systems to predict and analyze temporal signals. The best-known example is the Echo State Networks proposed by H. Jaeger in 2001, where the reservoir consists of a recurrent neural network. However, in recent years, other realizations have been proposed, in particular those in which the reservoir system can be implemented in hardware in a fast and energy-efficient manner (e.g., using optical components). Other recent developments concern the specific incorporation of prior (physical) knowledge about the source of the input signal (physics aware/informed Reservoir Computing) as well as various application examples in different disciplines. Therefore, the goal of this focus session is to highlight the rapidly advancing current developments in the field of Reservoir Computing in order to enable a direct scientific exchange between new methodological approaches and innovative applications.

Organized by Ulrich Parlitz (Göttingen), Kathy Lüdge (Ilmenau), and Christoph Räth (München)

Time: Thursday 15:00–18:00 Location: BH-N 243

Invited Talk DY 49.1 Thu 15:00 BH-N 243
Using reservoir computing to create surrogate models — •Lina Jaurigue — Technische Universität Ilmenau

Reservoir computing is a machine learning approach that utilizes the dynamics of a network or physical system to perform complex tasks while only training the output layer via linear regression. Due to the memory properties of the reservoir, reservoir computing is well suited to perform chaotic timeseries prediction tasks. When a reservoir is trained to perform one-step-ahead prediction of a chaotic trajectory, it can also be used to create a surrogate model for the system that the training trajectory originated from. This is done by feeding the output of the reservoir back in as input in the prediction phase. The resulting system is an autonomous dynamical system with solutions that depend on properties of the reservoir and the weights. We investigate how the properties of the reservoir, the input weights and the trained output weights influence solutions of the resulting autonomous dynamical system.

DY 49.2 Thu 15:30 BH-N 243
Image classification using collective modes of a two-dimensional array of photonic-crystal nanolasers — •Giulio Tirabassi[1], Kaiwen Ji[2], Cristina Masoller[1], and Alejandro Yacomotti[2] — [1]Departament de Fisica, Universitat Politecnica de Catalunya, Rambla Sant Nebridi 22, 08222 Terrassa, Barcelona, Spain — [2]Centre de Nanosciences et de Nanotechnologies, CNRS, Universite Paris-Sud, Université Paris-Saclay, 10 Boulevard Thomas Gobert, 91120 Palaiseau, France

Optical computing is revolutionizing the fields of Artificial Intelligence (AI) and High-Performance Computing (HPC) systems. Due to their ultra-low power consumption, nanolasers are ideal light sources for AI and HPC systems. In particular, two-dimensional photonic-crystal nanolaser arrays can be designed and fabricated with evanescent coupling, whose strength can be precisely controlled by adjusting the radius of the holes that separate adjacent nanocavities. In this work, we exploit the collective modes of nanolaser arrays of different sizes for binary classification of images and data. Using a dataset of hand-written digits (a standard dataset for assessing the performance of image recognition systems), we show numerically that an overall success rate of 98% can be achieved in digit classification. Finally, going beyond simulations, we show with laboratory experiments that the performance of the nanolaser arrays can be comparable to that of common non-linear classification algorithms.

DY 49.3 Thu 15:45 BH-N 243
Memristive devices for chaotic time series prediction — •Kristina Nikiruy[1], Seongae Park[1], Tzvetan Ivanov[1,2], Alon Ascoli[3], Fernando Corinto[4], Ronald Tetzlaff[3], and Martin Ziegler[1,2] — [1]Micro- and Nanoelectronic Systems, Department of Electrical Engineering and Information Technology, TU Ilmenau, Germany — [2]Institute of Micro- and Nanotechnologies MacroNano*, TU Ilmenau, Germany — [3]Faculty of Electrical and Computer Engineering, Institute of Circuits and Systems, TU Dresden, Germany — [4]Department of Electronics and Telecommunications (DET), Politecnico di Torino, Turin, Italy

Neuromorphic hardware, in which memristive devices are key elements, enables an energy-efficient and compact realization of the signal processing concept. Here we show that the application of nonlinear vector autoregression (NVAR), also known as next generation reservoir computing (NGRC), to a single-layer network with memristive weights can be used to predict signals, depending on the nature of the nonlinear functions and the number of weights. The network has been experimentally implemented with HfO2-based memristive devices and allows an accurate prediction of chaotic time series of Mackey-Glass and Duffing oscillators. The effect of the nonlinear combinations of the input data points, the network structure, and the number and nonlinear resistive switching properties of the memristive weights on the output response are studied. In this regard, it is shown how a suitable network structure can be tailored for chaotic time series prediction.

DY 49.4 Thu 16:00 BH-N 243
Computing Functionality in Gold Nanoparticle Networks — •Jonas Mensing[1], Andreas Heuer[1], and Wilfred G. van der Wiel[2] — [1]Institute of Physical Chemistry, University of Münster, Germany — [2]Center for brain-inspired Nano Systems, University of Twente, Enschede

Nanoparticles tunnel-coupled by insulating organic molecules exhibit strong nonlinear switching behavior at low temperatures. When assembling these switches in a recurrent network and manipulating the charge transport dynamics inside through surrounding electrodes, this network can be configured to execute brain-inspired computing applications. Via extensive kinetic Monte Carlo-based simulations we have analyze both stationary and time-dependent charge transport dynamics to assess the network*s computing and memory capabilities. We provide novel metrics to quantify general nonlinear properties of the network such as negative differential resistance and nonlinear separability of different input values, which are essential for future machine learning applications.

DY 49.5 Thu 16:15 BH-N 243
Reservoir computing of thermal convection: Random versus small-world networks — •Shailendra Kumar Rathor, Martin Ziegler, and Jörg Schumacher — Technische Universität Ilmenau, Germany

We study a classical two-dimensional thermal convection flow at a low Rayleigh number which is represented by an energy-conserving Lorenz-type model with eight degrees of freedom. This model accounts for the shear motion and tilted plumes in the flow. We employ a recurrent machine learning approach in the form of a reservoir computing model and test different reservoir architectures. In detail, small-world network architectures with different rewiring probabilities are compared with conventional random network topology. It is found that similar prediction capabilities are obtained on the basis of the mean squared error or the prediction horizon.

DY 49.6 Thu 16:30 BH-N 243
Forecasting Food Security with Reservoir Computing — •Joschka Herteux[1,2], Christoph Räth[1], Amine Baha[3], Giulia Martini[2], and Duccio Piovani[2] — [1]Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR) — [2]World Food Programme, Research, Assessment and Monitoring Division (RAM) — [3]World Food Programme Innovation Accelerator

Early warning systems are an essential tool for effective humanitarian action. Advance warnings on impending disasters facilitate timely and targeted response which help save lives, livelihoods, and scarce financial resources. We present a quantitative methodology based on Reservoir Computing (RC) to forecast levels of food consumption for 60 consecutive days, at the sub-national level, in four countries: Mali, Nigeria, Syria, and Yemen. The methodology is built on publicly available data from the World Food Programme's integrated global hunger monitoring system (https://hungermap.wfp.org/). We compare the performance of the RC model to various algorithms including ARIMA, XGBoost, LSTMs and CNNs spanning from classical statistical to deep learning approaches. Our findings highlight Reservoir Computing as a particularly well-suited model for this task given both its notable resistance to over-fitting on limited data samples and its efficient training capabilities. This work constitutes a successful application of RC on high-dimensional, heterogenous, real data and has been submitted to Nature Communications.

15 min. break

Invited Talk DY 49.7 Thu 17:00 BH-N 243

Opportunities in Quantum Reservoir Computing — •Roberta Zambrini — IFISC (UIB-CSIC)

Non-conventional computing inspired by the brain, (classical) neuromorphic computing, is a successful approach in a broad spectrum of applications, also burgeoning due to big data availability. Recent proposals go beyond classical substrates for quantum machine learning, as in Quantum Reservoir Computing. The classical version of this approach has been developed in the last 20 years and moving from classical to quantum physical reservoirs, has the potential to remarkably boost the processing performance in temporal tasks by exploiting quantum coherence, not requiring error correction. Furthermore this is naturally suited for fully quantum information processing (with quantum inputs). However, it also opens a series of new challenging questions, related to fundamental as well as implementation aspects. Examples are the identification of the best quantum regimes of operation, the role of statistics, or of quantum coherences and entanglement. After introducing the Quantum Reservoir Computing and showing how memory and non-linearity arise in a quantum formalism, we will discuss some of these issues, providing an overview of the field.

DY 49.8 Thu 17:30 BH-N 243

Exploring quantumness in quantum reservoir computing — •Niclas Götting[1,2], Frederik Lohof[1,2], and Christopher Gies[1,2] — [1]Institute for Theoretical Physics, University of Bremen, Bremen, Germany — [2]Bremen Center for Computational Material Science, University of Bremen, Bremen, Germany

With the advent of sophisticated semiconductor fabrication techniques for quantum photonic systems like coupled-cavity arrays, Quantum Reservoir Computing becomes a promising candidate to elevate Reservoir Computing (RC) to the next level. Not only does the phase space dimension of the quantum system scale exponentially with its size, the property of quantum entanglement also introduces a new resource to RC.

We investigate how these properties are linked to the Quantum Reservoir Computer (QRC) performance in simple benchmarks [1]. As the noisy intermediate-scale quantum (NISQ) devices of our current time are subject to various types of perturbations, we also analyze how dephasing of the quantum state affects the benchmark performance.

[1] N. Götting et al. Exploring Quantumness in Quantum Reservoir Computing. Phys. Rev. A 2023, 108 (5), 052427.

DY 49.9 Thu 17:45 BH-N 243

Enhancing the performance of quantum reservoir computing and solving the time-complexity problem by artificial memory restriction — •Saud Cindrak, Kathy Lüdge, and Lina Jaurigue — Institute of Physics, Technische Universität Ilmenau, Weimarer Str. 25, 98693 Ilmenau, Germany

We propose a novel scheme to optimize the performance and reduce the computational cost of quantum reservoir computing. In quantum reservoir computing, a quantum system serves as a reservoir and measurements are performed to obtain the expected values of observables. However, due to the state's collapse after measurement, computations must be repeated multiple times to construct expected values. This becomes challenging for timeseries tasks, where each new input requires the reinitialization of all prior inputs into the system, leading to quadratic time complexity. Another hurdle in reservoir computing lies in tuning nonlinearities. We address these challenges by artificially restricting the reservoir's memory, achieved by reducing the number of reinitialization time steps to a level below the fading memory capacity. With the proposed algorithm, we decrease the time complexity to linear and introduce an experimentally tunable parameter to change the nonlinear response. We demonstrate our approach on both an Ising reservoir and a quantum circuit reservoir and observe an increase in the information processing capacity and a reduction of the prediction errors for the Lorenz timeseries prediction task. [S. Cindrak, B. Donvil, K.Lüdge, L. Jaurigue, ArXiv:2306.12876 (2023). https://doi.org/10.48550/arXiv.2306.12876]