江苏科技大学

8th International Symposium on Recurrence Plots

August 21–23, 2019, Zhenjiang, China
Jiangsu University of Science and Technology

Programme Abstracts

http://symposium.recurrence-plot.tk

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Vice-President of Jiangsu University of Science and Technology
Dr. Wenxian Tang
Dean of School of Mechanical Engineering, Jiangsu University of Science and Technology
Dr. Hui Yang
Pennsylvania State University
Dr. Norbert Marwan
Potsdam Institute for Climate Impact Research
Dr. Charles L. Webber, Jr.
Loyola University Chicago

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Preparing materials and communicating with participants

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Dr. Yuankai Zhou
5 graduate students

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Coordination with local transportation, finance, hotel, volunteers and other services

Mr. Chunchun Zhai *Chair*
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Mr. Haibo Tan
10 graduate students

Sponsorship

Jiangsu University of Science and Technology The Pennsylvania State University

Aims

The objective of this Eighth Recurrence Plot Symposium is to encourage the exchange of knowledge and new ideas among scientists working in scientific disciplines of data analytics. Rapid advances in sensing, computing and communication technologies increasingly lead to the proliferation of "big" data. Recurrence plots and their quantifications are general methods for visualizing and analyzing complex-structured data for the new technological innovation and scientific discovery. After 30 years we continue to witness ongoing technical developments related to recurrence plots in both theoretical and practical domains. Some of these include: linkage of recurrence plots to network theory, inferences regarding directional couplings, identification of various spatio-temporal chaotic patterns, realization of tetherings across multiple scales of emergence, etc. Applications of recurrence plots are ever-expanding into such areas like engineering, mathematics, neuroscience, physiology, psychology, weather and climate patterns, financial systems, and linguistics. This symposium will provide a unique forum to facilitate the correlation of recent theoretical developments in recurrence

science with applications from various and diverse fields of inquiry. We welcome both theoretical and applied contributions that effectively implement recurrence plots, recurrence quantifications and their related methodologies.

We hope everybody will enjoy the meeting and find new inspirations and cooperations.

Location

The Symposium will be held in the Crowne Plaza Zhenjiang, No. 27 Changjiang Road, 212001 Zhenjiang, Jiangsu, China.

Lectures

Yonghe Ballroom, Location: Hotel third Floor

Practical Workshop

Boardroom, Location: Hotel second Floor

(participants should bring their own laptop)

Lunch

M Cafe, Location: Hotel First Floor

Social Events

Dinner, August 22

August 22 19:00, Yonghe Ballroom, Location: Hotel third Floor

Saturday, August 24

The signup for excursions will be at the registration desk. when you check in and get your symposium materials (name tag, booklet) On August 24th, we will offer a tour from early morning to the late afternoon. In the morning, we will visit the Slender West Lake in the Yangzhou city. After lunch, we will visit Jinshan Mountain and Xijin Ferry.

Internet Access

Wireless internet access will be available in the hotel. Individual access data will be provided at conference check-in.

Presentations

The speakers have to upload their presentation to the computer in the lecture hall in advance of their talk (in the morning of the day of their talk). The time for the talk is 17 min, plus 3 min discussion (invited talks are 40 min, plus 5 min discussion).

Both MacOS and Windows machines will be available, installed with standard presentation software (PowerPoint, Acrobat, Preview, and Keynote). You may also bring your own computer or presentation device provided that it is fitted with the appropriate VGA output and that you are capable of installing and testing the machine prior to the scheduled session time.

Collection of Presentations

We will provide a platform for sharing the presentations after the symposium in a secure way (password protected web site, secured pdf documents). We will ask the authors of the presentations to give a written permission for this purpose during the symposium. Without such a written permission, presentation files on the presentation computer will be deleted after the symposium.

Note

The symposium will adhere to the rules of good scientific and ethical practice. This means that it is not allowed to copy presentations from the presentation computer. It is also forbidden to take photographs of oral presentations and presented

posters without explicitely given permission of the presenter.

Oustanding Poster Award

All posters displayed at the meeting will be evaluated by a committee for an award recognizing excellence in presentation and significance in contribution to nonlinear science. The evaluation criteria comprise the poster display, the significance of the study, and the clarity of the oral presentation including the ability to answers questions.

Program

Tuesday, August 20th

15:00 Registration and excursion sign up (until 17:30)
Crown Plaza Hotel, 1st floor lobby

Wednesday, August 21st

8:00 Registration and excursion sign up
Crown Plaza Hotel, 1st floor lobby

9:00 Opening and welcome speech of the university president

Methodological Aspects

9:30 **Alessandro Giuliani**:
Keynote Lecture Recurrence Quantification Analysis and the quest for Science integration

10:15 **Magdalena Gregorczyk**, Andrzej Rysak:
Characterization of the fractional Rössler system dynamics by recurrence variables

10:35 **Andrzej Rysak**, Magdalena Gregorczyk:
Investigation of chaos-periodicity transitions in the Duffing system by recurrence analysis

10:55 *Group photo shoot & Coffee/tea break*

11:40 **Induja Pavithran**, Praveen Kasthuri, Abin Krishnan, Samadhan A. Pawar, R. I. Sujith, Rohan Gejji, William E. Anderson, Norbert Marwan and Jürgen Kurths:
Recurrence networks of spiky signals

12:00 **Yong Zou**, Reik V. Donner, Jürgen Kurths:
Analyzing long-term correlated stochastic processes by means of recurrence networks: Potentials and pitfalls

12:20 Qianshun Yuan, Shereha Semba, **Huijie Yang**:
Graphlet based time series analysis: A kinetic theory for Complex systems

12:40 *Lunch*

13:45 **Hui Yang**:
Keynote Lecture Heterogeneous recurrence analysis

14:30 **Cheng-Bang Chen**, Adam Meyers, Hui Yang, Soundar Kumara:
Generalized heterogeneous recurrence analysis of spatial data

14:50 **Charles L. Webber, Jr.**, James P. Hummel:
A Language Paradigm for Unifying Recurrence Plots and Quantifications Across Disciplines

15:10 *Coffee/tea break*

15:40 **K. Hauke Kraemer**, Norbert Marwan:
Border effect corrections for diagonal line based Recurrence Quantification Analysis measures

16:00 **Norbert Marwan**, K. Hauke Kraemer, Karoline Wiesner, Sebastian Breitenbach, Jens Leonhardt:
Recurrence based entropies

16:20 **Ayham Zaitouny**, David M. Walker, Michael Small:
Quadrant scan for multiple scale transition detection

16:40 Poster Session

Thursday, August 22nd

9:00 Welcome & miscellaneous announcements

Applications in Engineering

9:15 **R. I. Sujith**:
Keynote Lecture Analysis of Thermoacoustic Systems using Recurrence Plots

10:00 **Li-Ping Yang**, Timothy A. Bodiscoc, Ali Zareb, Richard J. Brown:
Effect of oxygenated fuels on the dynamics of combustion instabilities in a common-rail diesel engine

10:20 **Li-Yuan Wang**, Li-Ping Yang, En-Zhe Song, Chong Yao:
Analysis of the recurrence properties of the combustion fluctuations in a lean-burn SI natural gas engine

10:40 *Coffee/tea break*

11:00 **Dong Yang**:
Bridge Damage Detection under Moving Loads Based on Multi-Sensor Recurrence Plots

11:20 **Arkadiusz Syta**:
Nonlinear analysis of the helicopter main gear transmission vibrations using recurrences

Applications in Earth and Astro Sciences, Finance and Economics

11:40 **Reik Donner**, Georgios Balasis, Tommaso Alberti, Giuseppe Consolini, Jaqueline Lekscha:
Recurrence-Based Quantification of Multi-Scale Dynamical Complexity in the Earth's Magnetosphere

12:00 **I. A. Oludehinwa**, O. I. Olusola, O.S. Bolaji, O. O. Odeyemi:
Investigation of nonlinearity effect during storm time disturbance

12:20 *Lunch*

13:30 **Ondřej Kopáček**, Vladimír Karas:
Recurrence analysis of dynamics in black hole systems

13:50 **Shuixiu Lu**, Sebastian Oberst, Guoqiang Zhang, Zongwei Luo:
Capturing determinism buried in surrogate time series of dynamic pricing processes: Applying transition networks on order pattern plots

14:10 *Coffee/tea break*

Workshop

15:00 **Yun Chen**, Hui Yang:
Hands on session Heterogenous recurrence analysis software using MATLAB
(participants should bring their own laptop)

16:00 **George Datseris**:
Hands on session Fresh approach to dynamical systems software using Julia
(participants should bring their own laptop)

19:30 *Social Event: Dinner at Yonghe Ballroom (Hotel third Floor)*

Friday, August 23rd

9:00 Welcome & miscellaneous announcements

Applications in Life Science

9:15 **James Hummel**:
Keynote Lecture Potential roles for recurrence plots in understanding mechanisms of cardiac fibrillation

10:00 **Martin Calderon-Juarez**, Claudia Lerma, Aline Martinez-Martinez, Eduardo Quintanar, Felipe I Lopez-Trejo, Hortensia Gonzalez, Salvador Figuerola-Chaparro:
Recurrence plot analysis of short-term heart rate variability in fibromyalgia

10:20 **Fabio Leonelli**, Hui Yang:
Self-organizing visualization and pattern matching of vectorcardiographic

10:40 *Coffee/tea break*

11:00 **Mohammed Buqammaz**, Hui Yang:
Cross Recurrence Analysis of Nonlinear Interdependence Structures in Multivariate Data

11:20 **Radek Halfar**:
Investigation of cardiac tissue electrophysiology model using recurrence plots

11:40 **Zhongke Gao**:
Multivariate weighted recurrence network for analyzing SSMVEP signals to encode brain behaviors of EEG literate and EEG illiterate

12:00 **Leshao Zhang**, Patrick G.T. Healey:
xRQA for head nodding mimicry behaviour analysis in a VR monologue interaction

12:20 *Lunch*

13:30 **Ke Li**, Na Wei:
Dynamical Coordination of Hand Intrinsic Muscles for Precision Grip in Diabetes Mellitus

13:50 **Rashmi Bhardwaj**, Saureesh Das:
Recurrence Quantification Analysis of Tri-trophic Food Chain

14:10 **Hao Zengming**, Wang Jian:
Static Balance and Control Strategy in Children Aged 3 to 6 Years

14:30 **Ke Li**:
Recurrence Based Phase Synchronization Analysis of Digit Kinetic Signals During Precision Grip

14:50 Closing and poster award

15:00 Recurrence scholarship student reception, interaction, and award ceremony

17:30 *End*

Saturday, August 24th

Excursion

Poster

Poster 1 **Gertrudis H. González-Gómez**, Eduardo C. Quintanar-Izaguirre, Salvador Figuerola, Raul Martínez Memije, Héctor Pérez-Grovas, Marcos García, Claudia Lerma:
Dynamical Cardiorespiratory Interactions in End Stage Renal Disease

Poster 2 **Abhirup Banerjee**, Bedartha Goswami, Norbert Marwan, Bruno Merz, Jürgen Kurths:
Recurrence Analysis of Flood Events

Poster 3 **K. Hauke Kraemer**, Reik V. Donner, Jobst Heitzig, Norbert Marwan:
Recurrence threshold selection for obtaining robust recurrence characteristics in different embedding dimensions

Poster 4 **Arindam Mishra**, Abhirup Banerjee, Norbert Marwan, Syamal Dana, Jürgen KurthsM:
Recurrence Quantification Analysis of Synchronization, Chimera and Clustering in Ecological networks

Poster 5 **Leonardo L. Portes**, Arthur N. Montanari, Debora C. Correa, Michael Small, Luis A. Aguirre:
Reliability of Recurrence Network Analysis against the observability properties of the recorded time series

Poster 6 **Elena Pitsik**, Nikita Frolov, Vladimir Maksimenko, Alexander Hramov:
Recurrence quantification analysis of motor-related human electroencephalogram

Poster 7 **Shubo Lyu**, Andris Freivalds, Hui Yang, Stephen Piazza, Danielle Downs:
Validation of Standing Stability with Pendant-Based IMU Assessment Compared to a Sensor on the Lower Back Using Recurrence Quantitative Analysis

Poster 8 **Norbert Marwan**:
Co-authorship network of the recurrence plot domain

Poster 9 Jaqueline Lekscha, **Reik V. Donner**:
Areawise significance tests for recurrence network analysis

Abstracts

Recurrence Analysis of Flood Events *Poster*

Abhirup Banerjee[1,2], Bedartha Goswami[2], Norbert Marwan[2], Bruno Merz[3], Jürgen Kurths[2]

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Extreme hydro-logical events such as floods severely affect the communities living in the corresponding river basins and result in tremendous loss of property and wealth.

The aim of this work is to investigate flood behavior with respect to local effects, e.g. implementation of flood retention basins, and external controls by using recurrence analysis. Flood events occur at irregular time intervals and have a heavy tailed distribution, hence, such data often require data preprocessing and special methods able to analyze data with heavy tailed distribution. In this study, we use the edit

distance approach in combination with recurrence plots and recurrence quantification analysis to investigate flood events.

The edit distance approach allows us to use the recurrence-based characteristics to quantify how the dynamics of the flood occurrence has changed over time. We apply our approach to the river discharge data from the river Elbe and study the dynamical interactions of different variables such as precipitation, temperature and catchment wetness.

Recurrence Quantification Analysis of Tri-trophic Food Chain

Rashmi Bhardwaj, Saureesh Das

Guru Gobind Singh Indraprastha University, Mathematics, University School of Basic and Applied Sciences, New Delhi, IN
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In this paper the complex dynamics of tri-trophic ecological food chain model is analysed using techniques of nonlinear analysis and recurrence quantification analysis. The stability analysis is carried out to determine the equilibrium points of complex food chain and their parametric conditions of stability. Through numerical simulation the conditions of stability and evolution pattern of the complex system are validated and observed. Bifurcation analysis is then carried out to analyse the transition of system's dynamic behaviour from regular to chaotic state. Lyapunov exponents are evaluated to confirm the existence of chaos in system dynamics. Recurrence plots and recurrence quantification analysis based measures – recurrence rate, determinism, divergence, entropy, laminarity and trapping time, are used to detect transitions between periodic and chaotic states and also the laminar states of the complex three species food web model with improved growth rate function and predatory ability. The study of dynamical equation of such a complex biological system with transients in terms of these measures results in localization of bifurcation behavior of the system.

Cross Recurrence Analysis of Nonlinear Interdependence Structures in Multivariate Data

Mohammed Buqammaz, Hui Yang

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The technological advancement we are witnessing in devices and gadgets coupled with increasing capabilities of data storing and sharing have immensely contributed to the proliferation of "Big Data". Therefore, there is an increasing need for new methodologies to dig deep through data sets and extract meaningful conclusions and hence make decisions that are based on solid scientific structure. Failing to address this need for such methodologies will result in missing precious opportunities to achieve great benefits to organizations and squander great amount of data, as it remains piled in storage. Motivated by Marwan and Kurths' Cross Recurrence Plot (CRP), we intend to further develop that methodology in order to overcome its current limitations. Moreover, we aim to provide new cross-recurrence methodologies to study nonlinear interdependence, where we first test the proposed model with simulated data, and then verify its capability with real data collected from healthcare systems. The significance of this research can be summarized in modifying current CRP methodology in addition to providing physicians new and improved means to monitor cardiac signals.

Recurrence plot analysis of short-term heart rate variability in fibromyalgia

Martin Calderon-Juarez, Claudia Lerma, Aline Martinez-Martinez, Eduardo Quintanar, Felipe I. Lopez-Trejo, Hortensia Gonzalez, Salvador Figuerola-Chaparro

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Fibromyalgia is an illness characterized by chronic widespread pain, sleep disturbances and physical exhaustion. The autonomic nervous system function is affected in these patients, which is associated to increased pain sensitisation. Heart rate variability (HRV) analysis in 24 hours recordings has shown autonomic dysfunction in fibromyalgia patients during daily routine activities. In controlled conditions, such as active standing, changes in the autonomic balance have been identified by linear HRV indices and recurrence plot (RP) indices in other pathologies and healthy people.

The aim of this work was to we evaluate the effect of the orthostatic challenge test (active standing) in HRV of women with fibromyalgia with quantitative RP analysis. We obtained 33 electrocardiogram (ECG) recordings from 22 women with fibromyalgia and 21 recordings from 13 healthy controls. Ten minutes were recorded with each participant in supine position (SP) followed by ten minutes during active standing (AS). After identification of every heartbeat within the ECG, 5-minutes length HRV time series were obtained in each position. We calculated the RP indices with an embedding dimension = 7, embedding delay = 1 or ad hoc (estimated with the autocorrelation function), and norm fan (fixed amount of neighbours) or rr (fixed recurrence rate), and threshold = 0.07. RP indices were compared with ANOVA for repeated measures.

Regarding differences between fibromyalgia and controls, during AS determinism was lower and recurrence time type 1 (T1) was higher in fibromyalgia compared with controls (delay = 1, rr). There were no differences in other indices. In response to AS, all indices based on vertical lines and recurrence time type 2 (T2) increased in both fibromyalgia and control groups (compared to SP), regardless of the RP parameters. There were few changes in diagonal indices (determinism and Lmax) with delay = 1 and rr. When the norm rr and delay ad hoc were applied, all vertical indices, diagonal indices, laminarity and T2 decreased. When fan norm was applied, there were no differences between estimations with delay = 1 and ad hoc delay. When delay = 1 was applied in both norms, all indices increased when using rr, but not with fan.

In conclusion, HRV RP indices based on verticals and T2 increase in response to AS. There were few differences in RP indices between fibromyalgia patients and controls, suggesting preserved short-term cardiovascular regulation in fibromyalgia. RP indices estimation with short-term HRV recordings depends greatly on the RP parameters.

Generalized heterogeneous recurrence analysis of spatial data

Cheng-Bang Chen, Adam Meyers, Hui Yang, Soundar Kumara

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Recurrence plot is one widely used tool to represent the patterns of recurrence dynamics, and further facilitate the quantification of recurrence patterns, namely recurrence quantification analysis. It is noted that the complex nonlinear dynamical recurrences not only exhibit in the temporal data but also in the spatial domain. To delineate the recurrence dynamics of the spatial data, prior efforts either extended the recurrence plot to a four-dimensional hyperspace for spatial recurrences or utilized the weighted network structure to characterize the spatial recurrence patterns. However, these works treated all recurrences homogeneously that rich information embedded on the heterogeneous states are not fully explored in the spatial domain. Therefore, we propose a novel approach utilizing the space-filling curve and fractal representation to quantify the heterogeneous recurrences of the spatial data. A spatial data contains two essential components, which are the spatial location, and the corresponding attributes. The proposed method first leverages the Hilbert Space-Filling Curve to index the multi-dimensional spatial locations into one-dimensional space. Then, the corresponding spatial attributes are converted to a discrete state sequence utilizing the state space representation. Then, with the Iterated Function System (IFS) transformation, each point of the state sequence is mapping to a unique address of a two-dimensional space that the address embeds the information of all previous transitions. Thus, we leverage the features of IFS address to characterize the heterogeneous recurrence behaviors of spatial data. Furthermore, we develop five new heterogeneous recurrence quantification analysis (HRQA) to quantify the heterogeneous recurrences in various aspects. Experimental results in both simulation and real-world case studies show that the proposed approach yields superior performance in the extraction of salient features to characterize recurrence dynamics in spatial systems.

Fresh approach to dynamical systems software using Julia *Workshop*

George Datseris

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Julia is a relatively new computer programming language that has an impressive list of features: dynamic, intuitive syntax, multiple dispatch, performance approaching C/FORTRAN and being open source. Due to these features many large- and small-scale organizations have switched to Julia as their main simulation tool. DynamicalSystems.jl is an award-winning Julia software library for the exploration of chaos and nonlinear dynamics. It offers a fresh approach to simulating dynamical systems because it was built from the ground up with the principles of clarity, intuition and robustness. In the first part of this workshop I will be introducing the Julia language and its capabilities, while trying to compare with the most popular competitor, Python. In the second part I will be overviewing DynamicalSystems.jl and focus a bit more into the package 'RecurrenceAnalysis' (lead dev. by Helios de Rosario) which is the latest addition to DynamicalSystems.jl.

Recurrence-Based Quantification of Multi-Scale Dynamical Complexity in the Earth's Magnetosphere

Reik Donner, Georgios Balasis, Tommaso Alberti, Giuseppe Consolini, Jaqueline Lekscha

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The Earth's magnetosphere is characterized by a considerable degree of dynamical complexity resulting from the interaction of different multiscale processes, which can be both directly driven/triggered by changes of the interplanetary medium condition, and due to internal processes of the magnetosphere. This complexity can be characterized by following both "classical" and "new" dynamical system tools. Recent work has demonstrated that recurrence plot based techniques may play a pivotal role in such an assessment.

Here, we present some recent results on applications of recurrence quantification analysis and recurrence network analysis to different geomagnetic indices (Dst, SYM-H, ASY-H, AE) reflecting the variability of the Earth's electromagnetic environment at different time-scales and magnetic latitudes. In addition, we also apply the same techniques to some essential properties of the solar wind which are believed to have a relevant effect on geomagnetic field fluctuations and might serve as triggers of instability leading to geospace magnetic storms and/or magnetospheric substorms. Our findings underline that dynamical fluctuations of the geomagnetic field during periods of magnetospheric quiescence and storminess indeed exhibit distinctively different levels of dynamical complexity. Moreover, we provide additional evidence for a time-scale separation in magnetospheric dynamics that is further characterized by employing some multiscale version of recurrence analysis utilizing a continuous wavelet transform of the signals of interest. Our corresponding findings are of potential relevance for the development of improved approaches for space weather modelling and forecasting.

Multivariate weighted recurrence network for analyzing SSMVEP signals to encode brain behaviors of EEG literate and EEG illiterate

Zhongke Gao

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Recently, Steady State Motion Visual Evoked Potential (SSMVEP)-based Brain Computer Interface (BCI) has attracted a lot of attention. In this paper, we designed a SSMVEP-based BCI system, in which we applied a ring-shaped motion checkerboard pattern to realize SSMVEP stimulation. Then we conducted SSMVEP experiments to obtain electroencephalogram (EEG) signals from 8 subjects, including 4 EEG literates and 4 EEG illiterates. Thereafter, we use the Canonical Correlation Analysis (CCA) and Support Vector Machine (SVM) method to verify the effect of individual differences on SSMVEP signal classification. We find that the classification accuracies of EEG illiterates are relatively lower than that of EEG literates. Thus – in order to investigate the differences of brain cognitive processes between the two groups of subjects, we construct a multi-weighted recurrent network and calculate the integrated weighted local efficiency and clustering coefficient of the two groups. We find that in the SSMVEP experiment, the two groups have significant differences in these two network indicators. The results demonstrate that our method enables to characterize the cognitive difference between EEG literates and EEG illiterates. At the same time, our method provides a novel insights into the cognitive behavior of the brain.

Recurrence Quantification Analysis and the quest for Science integration

Alessandro Giuliani

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The devastating information crisis that biomedical sciences are experiencing, together with the stagnation of theoretical physics, ask for a global and radical re-shaping of scientific culture.

In year 2000 Robert Laughlin and David Pines, aptly proposed a way out from the crisis by means of a paradigm shift replacing focus on "shared microscopic bricks" with the focus on "shared organizing principles". In [1] they state: "The emergent physical phenomena regulated by higher organizing principles have a property, namely their insensitivity to microscopic that is directly relevant to the broad question of what is knowable in the deepest sense of the term". The authors call the spatial and temporal scales where we can discover these organizing principles "The middle way" [2].

The quest for organizing principles insensitive to microscopic details translates into the elucidation of correlation structures in both time and space that cannot be derived from first principles. In the case of biomedical sciences, this implies the lack of reproducibility of molecular biology [3] derives from the positioning of research at a too microscopic, noise dominated, layer (e.g. genes) forgetting the scale where organizing principles live (e.g. gene networks).

In order to put into practice the above theoretical issues we need mathematical tools that can survive in a still unexplored territory with no possibility to rely on basic principles and firm theoretical hypotheses. Recurrence Quantification Analysis is one of the most suited quantitative tools to go into the new science of "mesoscopic organization principles" for its focusing on correlation, independence from stationarity constraints, and ability to keep track of singularities. Moreover, the simplicity of the underlying mathematics (we can collapse to Pythagora theorem) creates a common playground for different science fields from psychology to physics and engineering so offering the key to go out from the ultra-specialization that is drastically limiting the progress of knowledge.

References:

[1] Laughlin, R. B., Pines, D. (2000). The theory of everything. Proceedings of the National Academy of Sciences, 97(1), 28-31.

[2] Laughlin, R. B., Pines, D., Schmalian, J., Stojković, B. P., Wolynes, P. (2000). The middle way. Proceedings of the National Academy of Sciences, 97(1), 32-37.

[3] Ioannidis, J. P. (2005). Why most published research findings are false. PLoS medicine, 2(8), e124.

Dynamical Cardiorespiratory Interactions in End Stage Renal Disease *Poster*

Gertrudis H. González-Gómez[1], Eduardo C. Quintanar-Izaguirre[2], Salvador Figuerola[3], Raul Martínez Memije[4], Héctor Pérez-Grovas[4], Marcos García[4], Claudia Lerma[4]

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Variability among the intervals of consecutive heartbeats (HRV) is produced mainly by the changing influences of the autonomous nervous system, and by the fundamental regulation of the respiratory arrhythmia. In previous works we have shown that in end-stage renal disease (ESRD) patients despite the stressed condition that they face, that leads to an overexpression of the sympathetic activity, they can display regulatory responses to diverse physiological stimuli like active standing (AS) and even to the very demanding periodic hemodialysis sessions (HD). We also have shown with Analysis of Diagonals of CRP that is possible to recognize very notable differences in the dynamics of interaction between HRV and systolic blood pressure in healthy subjects between supine position and AS.

In this work, we explored for the first time the interactions between HRV and breathing amplitude using CRP Quantitative Analysis and Analysis of Diagonals of CRP. We compared two patterns of paced respiration (CB1, CB2) in ESRD patients before and after HD, as well as two types of stimuli: AS, which requires quick adjustment to redirect the blood to the brain, and HD, which induces critical changes in circulating blood volume. ECG and simultaneous breath amplitude recordings were obtained from ten ESRD patients and eleven healthy subjects using a Zephyr BH3 device. We acquire continuous records for close to forty minutes. Using a customer developed routine we obtained the R to R intervals and its matching breath amplitude. We got the embedding delay using Cross-Correlation and the embedding dimension with

False Nearest Neighbor algorithm. We achieved the corresponding CRP and ten indices. We also obtained the indices for the Analysis of Diagonals.

ESRD patients exhibited higher vertical indices during CB2 post HD than before HD. In both groups, vertical indices were larger during CB1 and CB2 compared with spontaneous respiration during supine position or AS. Compared to the control group ESRD patients showed lower diagonals indices during supine position before HD and during CB1 after HD. The Analysis of Diagonals showed more dispersion in the diagonal indices of ESRD patients compared to healthy subjects in any condition, suggesting a decreased cardiorespiratory interaction in ESRD patients.

Characterization of the fractional Rössler system dynamics by recurrence variables

Magdalena Gregorczyk, Andrzej Rysak

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The paper presents the results of a study on the dynamics of a Rössler system described by a set of fractional differential equations. In the study, the RP method is used to assess changes in the system dynamics resulting from changes in the values of its parameters and orders in the set of governing equations.

Two main cases are analyzed. In the first one, a classical system with integer derivatives (q_n) of differential equations is considered, with a periodic window obtained by evolution of the a system parameter. Then, some orders q_n of the derivatives are modified to fractional values, and numerical methods are applied to both detect and assess the influence of system fractionality on its dynamics.

In the second case, both integer and fractional systems are analyzed with periodic windows triggered by evolution of the a and q_n parameters, respectively. Results of the two analyzed cases of the Rössler system are compared in order to pinpoint the differences in the system dynamics in chaos-periodicity transition regions, caused by changing the system's parameters and fractionality.

Evaluation of the dynamics of the analyzed integer and fractional systems provides recursive variables which are interpreted in relation to other methods, including bifurcation diagrams and Lyapunov exponents.

Investigation of cardiac tissue electrophysiology model using recurrence plots

Radek Halfar

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Since Ischaemic heart disease is the world's biggest killer [WHO, The top 10 causes of death. Online; accessed 10-May-2018] the investigation of cardiac tissue is a crucial task, that researchers among the world facing. One of the possible ways of this investigation is using mathematical models of this tissue. There are many well established cardiac cell models. In this paper, the Fenton-Karma model is used.

This model was introduced in 1998 [Fenton, Flavio & Karma, Alain. Vortex dynamics in three-dimensional continuous myocardium with fiber rotation: Filament instability and fibrillation. Chaos (1998).] and since then it was used in many scientific works. An example is an article written by Allexandre Otani [Allexandre, N. Otani. Preventing alternans-induced spiral wave breakup in cardiac tissue: An ion-channel-based approach. Phys. Rev. E (2004)]. In this paper, the author studied the electrophysiological and dynamic mechanism of spiral waves break up.

In this work, 2D Fenton-Karma cardiac tissue model based on code published by Hiroshi Ashikaga [Ashikaga, H. http://github.com/ashikagah/Fenton-Karma/] is used. Model equations were solved using a finite difference method for spatial derivatives and explicit Euler integration for time derivatives. Newman boundary conditions are assumed. The modelled tissue was 12.5×12.5 cm with resolution 0.025 cm. The equations were solved from 0 to 40 s with a resolution of 0.1 ms. The model was stimulated with a rectangular pulse with an amplitude of 0.5 and duration 1 ms. The spatial size of the stimulus was 0.25×0.25 cm (given in the middle of the modelled tissue). The individual pacing pulses were separated by stimulation delay (c) from 15 to 125 ms. To eliminate transients, the resulting transmembrane potential from 20 sec to 40 sec in 10 ms steps was further analysed.

Next, a new variable (x) was created from the matrices representing the distribution of transmembrane potential in the tissue (u). This variable was computed as follows:

$$x(t) = \sum_{i=1}^{N} \sum_{j=1}^{N} (u_{i,j}(t)),$$

where i, j are matrix indices and N is the total number of rows/columns. After that, the estimation of proper time lag and embedding dimension was made. Finally, the

recurrence plots and recurrence quantification analysis were computed. These calculations were performed in R designed by R Core Team using packages *R.matlab* [Henrik Bengtsson et al., 2018], *nonlinearTseries* [Constantino A. Garcia, Gunther Sawitzki, 2019], and *fractal* package [William Constantine, Donald Percival, 2017].

From the results, the periodic, as well as non-periodic motions resulting from periodic stimulation, can be seen.

Potential roles for recurrence plots in understanding mechanisms of cardiac fibrillation

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Fibrillation refers to rapid chaotic electrical activity leading to ineffective contraction and may arise in the atria or ventricles of the human heart as an end result of numerous disease processes. Fibrillation can be initiated and maintained by rapidly firing focal sources or spiral wave reentry with fibrillatory conduction to the rest of the chamber. It can also be sustained by more diffuse processes supporting the substrate for multiple wavelet reentry. Recurrence plots derived from electrograms during fibrillation may identify areas harboring focal sources, which if present, may display periodicity amid the chaotic dynamics present in the remaining passively activated chamber. Identification of the underlying mechanism involved allows for optimization of ablative and pharmacologic treatment in the individual patient.

Recurrence analysis of dynamics in black hole systems

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Several applications of recurrence analysis in the context of astrophysics of compact objects (black holes or neutron stars) are reviewed. Extreme gravity of such objects causes strong curvature of the spacetime which supports non-linear effects and possible emergence of chaotic dynamics of matter in their vicinity. Observed signals (both electromagnetic and gravitational wave) from these objects may thus be affected by chaotic motions in the source system. Recurrence analysis is applied to detect chaos in simulated data and possible applications on observational data are being considered.

Border effect corrections for diagonal line based Recurrence Quantification Analysis measures

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Recurrence quantification analysis (RQA) is a powerful tool for the identification of characteristic dynamics and of regime changes. This approach is successfully applied in many scientific disciplines. Several measures of complexity are defined onÂăfeatures (such as diagonal and vertical lines) in the recurrence plot (RP), which represents time points j when a state $\vec{x}_i$ at time i recurs. These line structures represent typical dynamical behavior and can be related to certain properties of the dynamical system, e.g., chaotic or periodic dynamics. Therefore, their quantitative study by the RQA measures within sliding windows is a frequently used task for the detection of regime changes. However, as some RQA measures rely on the probability distribution of the lengths of the diagonal lines in an RP, the artificial alteration of these lines due to border effects, insufficient embedding, or a certain sampling setting can have a significant impact on these measures. A few ideas have been suggested to overcome the mentioned problems. Here we review these ideas, propose novel correction schemes, and systematically compare them.

Specifically, we investigate the proper estimation of the diagonal line length entropy for exemplary systems (discrete and continuous). We propose corrections schemes, which yield less biased estimates, especially under noise.

Recurrence threshold selection for obtaining robust recurrence characteristics in different embedding dimensions *Poster*

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The appropriate selection of recurrence thresholds is a key problem in applications of recurrence quantification analysis and related methods across disciplines. Here, we discuss the distribution of pairwise distances between

state vectors in the studied system's state space reconstructed by means of time-delay embedding as the key characteristic that should guide the corresponding choice for obtaining an adequate resolution of a recurrence plot. Specifically, we present an empirical description of the distance distribution, focusing on characteristic changes of its shape with increasing embedding dimension. Our results suggest that selecting the recurrence threshold according to a fixed percentile of this distribution reduces the dependence of recurrence characteristics on the embedding dimension in comparison with other commonly used threshold selection methods. Numerical investigations on some paradigmatic model systems with time-dependent parameters support these empirical findings.

Areawise significance tests for recurrence network analysis

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Many time series analysis techniques utilize sliding window approaches or are repeatedly applied over a continuous range of parameters. When combined with a significance test, intrinsic correlations among the results can make falsely positive significant points appear as continuous patches rather than as isolated points. To account for this effect, we present an areawise significance test that identifies such false positive patches. For this purpose, we numerically estimate the decorrelation length of the statistic of interest by calculating correlation functions between the analysis results and require an areawise significant point to belong to a patch of pointwise significant points that is larger than this decorrelation length. We apply our areawise test to results from windowed traditional and scale-specific recurrence network analysis in order to identify dynamical anomalies in time series of a non-stationary R"ossler system and tree ring width index values from Eastern Canada. Especially in the palaeoclimate context, the areawise testing approach markedly reduces the number of points that are identified as significant and therefore highlights only the most relevant features in the data. This provides a crucial step towards further establishing recurrence networks as a tool for palaeoclimate data analysis.

Self-organizing visualization and pattern matching of vectorcardiographic

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The Electrocardiogram (ECG),the most commonly performed cardiac test, is often analyzed by computerized tracing interpretation. Diagnostic accuracy of these automated systems is low requiring over reading by a qualified physician. Existing ECG algorithms focus on a time-scale representation of cardiac electrical events ignoring information contained in the spatial distribution of the ECG. Vectorcardiography (VCG) extrapolates from standard ECG the magnitude and direction of the electrical forces generated and represents them as a continuous series of vectors that form curving lines around a central point. 3D VCG therefore adds space-time information defining with more precision the abnormalities of electrical propagation in conditions such as left bundle branch block (LBBB) or anterior myocardial infarction (MI). We tested the hypothesis that subjects with similar pattern of depolarization should share similar 3D VCG loops. The 12-lead digitized ECGs from 93 patients, equally divided among normal control (N), LBBB and MI were retrospectively collected, and a generalized Dower transform was used to synthesize 3-lead VCG. Initial evaluation of time-domain X, Y, Z ensembles of 3-lead VCG of the three groups shows that QRS time durations yields a skewed distribution and means and standard deviations are not sufficient to differentiate the groups. On the contrary, QRS loops of 3D VCG yield different spatiotemporal paths for the groups including 3D morphology, area, length (i.e., QRS time duration) and angle (i.e., electrical axis). A composite measure of pattern dissimilarity through pattern matching of 3D VCGs was developed. Patients were treated as nodes in the network and dissimilarity distance between 3D VCG waveforms as the weights of edges. The scatter plot of nodes of the entire group derived on the basis of dissimilarity matrix among patients shows that this self-organization of 3D QRS patterns accurately differentiates the three distinct groups. There is only one healthy subject falling into the MI anterior septal group. Such experimental results show that (i) each cardiac condition shares similarities of cardiac electrical activity within its own group, but yields bigger dissimilarities from other groups; (ii) such pattern similarities and dissimilarities could be leveraged to visualize the clustering of subjects (iii)an automated algorithms based on pattern matching of VCGs effectively groups ECGs with different pathologies obviating the need for human supervision improving the standard systems based on classification (i.e., supervised learning and training).

Dynamical Coordination of Hand Intrinsic Muscles for Precision Grip in Diabetes Mellitus

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This study investigated the effects of diabetes mellitus (DM) on dynamical coordination of hand intrinsic muscles during precision grip. Precision grip was tested using a custom designed apparatus with stable and unstable loads, during which the surface electromyographic (sEMG) signals of the abductor pollicis brevis (APB) and first dorsal interosseous (FDI) were recorded simultaneously. Recurrence quantification analysis (RQA) was applied to quantify the dynamical structure of sEMG signals of the APB and FDI; and cross recurrence quantification analysis (CRQA) was used to assess the intermuscular coupling between the two intrinsic muscles. This study revealed that the DM altered the dynamical structure of muscle activation for the FDI and the dynamical intermuscular coordination between the APB and FDI during precision grip. A reinforced feedforward mechanism that compensates the loss of sensory feedbacks in DM may be responsible for the stronger intermuscular coupling between the APB and FDI muscles. Sensory deficits in DM remarkably decreased the capacity of online motor adjustment based on sensory feedback, rendering a lower adaptability to the uncertainty of environment. This study shed light on inherent dynamical properties underlying the intrinsic muscle activation and intermuscular coordination for precision grip and the effects of DM on hand sensorimotor function.

Recurrence Based Phase Synchronization Analysis of Digit Kinetic Signals During Precision Grip

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Precision grip plays a key role in a variety of manual functions. Development of digit coordination quantification provides a novel avenue for diagnosis of peripheral neuropathies, which are usually associated with sensorimotor deficits on the hand. Phase synchronization (PS) is a critical feature of coupled signals. An advanced PS estimation has been proposed based on the cross recurrent quantification analysis (CRQA), This recurrence-based PS is a nonlinear approach that shows reliability in quantifying the phase synchronization of coupled non-stationary signals. The objective of the current study was to quantify the phase synchronization of digit kinetic signals when the thumb coordinates with the index finger for precision grip. We hypothesized that the compromised tactile sensitivity will lead to a change of phase synchrony across digits.

Capturing determinism buried in surrogate time series of dynamic pricing processes: applying transition networks on order pattern plots

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Demand volatility is the most critical progenitor of a dynamic pricing strategy (Dps) that timely prices the good or service based on the realisation of the demand. Stochastic demand is widely assumed in the study of an optimal Dps, assuming dominant high-dimensional processes, whereas deterministic, low-dimensional chaotic processes with random-like behaviour are usually neglected. Consequently, the volatility arising from deterministic processes in dynamic pricing has received negligible attention to date especially when the demand is contaminated by noise or if it is slightly non-stationary (Kantz and Schreiber, 2004; Zou et al., 2019). However, only knowledge of deterministic processes would allow explicitly modelling and give the bounded demand to mitigate the volatility related to modelling errors, contributing to attaining an optimal control – important for vendors and consumers (Talluri and Van Ryzin, 2006).

Here, we construct a transition network based on the phase space of order patterns to define determinism buried in a surrogate time series of dynamic pricing processes. The network characteristics are based on the mean and the median of order patterns (Lu et al. 2018). The surrogate time series is either derived from a random shuffle of a model of a deterministic dynamic pricing process, which mimics a random process (Gaussian noise), or from a random change of a bifurcation parameter within the mode, which is to simulate the influence of non-stationarity.

Our results show that network characteristics can be used to detect the degree of determinism contained in the time series with different levels of randomisation for a surro-

gate. In comparison with the recurrence network, the ordinal partition transition network and permutation entropy, the characteristics based on the transition matrix of order patterns give good discrimination of dynamic pricing processes with a random change of the bifurcation parameter and Gaussian noise. These results emphasise the potential of transition networks applied to order patterns to unveil determinism buried in a real demand signal.

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Validation of Standing Stability with Pendant-Based IMU Assessment Compared to a Sensor on the Lower Back Using Recurrence Quantitative Analysis *Poster*

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Recurrence quantification analysis (RQA) has been widely implemented as a nonlinear tool in multiple research areas, and human body balance study is one of them. Previous studies have suggested that the dynamic features provided by RQA of body'ÂĂs center of mass (COM) is reliable in distinguishing balance disorders using inertial measurement units (IMUs). The most common area for putting the IMU is on subject's lower back with a belt, for it is the location where is nearest to the COM. However, wearing a sensor like this for some specific populations like pregnant women may be challenging due to discomfort and lack of fit. In this research, a novel pendant IMU sensor was designed, which was worn around neck, and compared with the sensor on the lower back. There were three types of standing tasks: double-leg, tandem, and single-leg standing. In order to induce instability, each task was performed in eyes open and eyes closed conditions. Six RQA measurements (%recurrance, %deterministic, linemax, entropy, %laminarity, trapping time) were used for data analysis. The objective of this research is to validate whether the pendant sensor can distinguish different balance conditions better than the lower back sensor using the RQA measurements.

Recurrence based entropies

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Dynamical processes in Earth Sciences are generally considered to be of complex nature. The term complexity is frequently used for processes that are either unpredictable (e.g. nonlinear dynamics), consist of many different components, or exhibit regime transitions (e.g. tipping points). To measure complexity, the Shannon entropy is mainly used.

Here we present various entropy measures that have been defined on the base of the recurrence plot. Because of the different features used, these entropy measures represent different aspects of the analysed system and, thus, behave differently. In the past, this fact has lead to difficulties in interpreting and understanding those measures. We summarize the definitions, the motivation and interpretation of these entropy measures, compare their differences and discuss some of the pitfalls when using them.

Finally, we illustrate their potential by applying them on a speleotheme-based palaeoclimate record from Blessberg Cave (Germany). Using entropy measures, the alternating influence of continental versus maritime climate in past central Europe can be identified.

Co-authorship network of the recurrence plot domain *Poster*

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A presentation of the co-authorship network of publications on recurrence plots, recurrence networks and recurrence quantification analysis.

Recurrence Quantification Analysis of Synchronization, Chimera and Clustering in Ecological networks *Poster*

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We study a globally coupled ecological network where each node (patch) is governed by a modified Rosenzweig-MacArthur (RM) model consisting of predator and prey species. The interaction between the patches is through a weighted mean-field diffusion. Particularly for low values of weighting factor of the mean field diffusion and varying coupling strength of both the species, the network shows

1. homogeneous steady states (HSS), all the patches converge to identical steady state,
2. 1-cluster:complete synchrony
3. 2-cluster states: all the patches organize them into two clusters. Populations in each cluster grow or oscillate coherently in time, but no coherence exists between the patches in clusters. Note that number of patches in each cluster is not identical.
4. 3-cluster states: populations organize in three clusters of patches. Populations in each cluster are synchronized, but no synchrony between the patches in different clusters.
5. 4-, 5-cluster states: the whole population is organized them into multiple clusters. Same conditions persist as elaborated for 2-, 3-clusters.
6. Chimera states: the patches organized them into two sub-clusters, one coherent and another incoherent. Populations are all synchronized in patches of the coherent cluster; populations have no synchrony in patches of the incoherent cluster.

In our study, we want to use multivariate recurrence analysis to characterize the homogeneous states emerging from the coupled network. We would like to explore cross recurrence plot for determining the chimera states that exist in patches. Most importantly, we would like to quantify the clustered states which has not been studied yet from recurrence plot. In a broad sense, we would like to use the multivariate recurrence plot to differentiate synchronization , cluster states and chimera states emerging in population dynamics. To test our proposition we use the ecological model defined above revealing their underlying dynamics in patches.

Investigation of nonlinearity effect during storm time disturbance

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We examine the nonlinearity effect in the Disturbed Storm Time (Dst) signals during minor, moderate and major geomagnetic storm between the year 2008 and 2016 using Recurrence Plot (RP), Recurrence Rate (RR) and Approximate Entropy (ApEn). The dynamics of the Dst signals behave in stochastic path during the minor geomagnetic stormy period and in deterministic path during increasing geo- magnetic stormy period. As the geomagnetic storm increases, the RP showed more deterministic structure indicating that it possesses the potential to detect geomagnetic storm event even at the infinitesimal impact of the geomagnetic storm. The dynamical behaviour is reflected in the RR as the geomagnetic storm intensifies. The occurrence of geomagnetic storm associated with significant Dst signal and monthly average RR is prevalent during the beginning year (2012) of the high solar activity than the peak year (2014) of the high solar activity. Our results show that higher average RR is not consistent throughout the equinoctial season between the year 2008 and 2016.

Recurrence networks of spiky signals

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Thermoacoustic instability is a challenging problem faced in gas turbines and rockets. It is a state of self-sustained large amplitude periodic oscillations arising due to the positive feedback between the unsteady heat release rate oscillations and the acoustic field in a confinement. The large amplitude oscillations occurring during thermoacoustic instability are detrimental and their presence can lead to increased heat transfer, violent vibrations causing fatigue failure of the components and even mission failure in rockets. Thermoacoustic system involves interac-

tion between processes at different timescales and length scales leading to complex spatio-temporal dynamics.

In order to study the transitions to such oscillatory instabilities in a complex system, we use a complex networks approach. Complex network is an efficient tool to study systems composed of different interacting entities. Various types of networks have been used in literature such as correlation networks, visibility graphs, recurrence networks, cycle networks, etc. Among these networks, recurrence-based complex networks (RNs) provide information about the topology of the attractor in high dimensional phase space. We can interpret the characteristics of the networks in terms of geometric properties of the phase space.

In the present work, we construct recurrence networks from the time series of acoustic pressure fluctuations obtained during different dynamical regimes from a liquid rocket combustor. We notice that the dynamics of acoustic pressure during thermoacoustic instability is akin to a spiky periodic signal. Such behaviour of the pressure signal is in contrary to the sinusoidal variation observed during thermoacoustic instability in gas turbine combustors. Previous studies have shown that the RN during thermoacoustic instability in gas turbines display a ring-like structure. We unravel a different pattern in RN for a rocket combustor which shows protrusions at different locations on the ring-like structure. These extra patterns are found to be exhibited due to the spiky nature of the time series. We create synthetic time series similar to the experimental data to explain this particular topology. The reconstructed phase space of such largely unexplored signals allows us to get deeper insights about the underlying dynamics of the system. Further, complex networks based on recurrences are an appropriate method for analysing highly nonlinear, high dimensional complex systems.

Recurrence quantification analysis of motor-related human electroencephalogram *Poster*

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Analysis of motor-related activity in human brain is a challenging task lying on a junction of neuroscience, applied mathematics and robotics. Great scientific interest to this topic is caused by its practical applications in such socially important areas as neurorehabilitation and neuroprosthetics. In this context, analysis of brain activity signals aimed at detecting motor imagery, motor attempt and actual motor execution patterns and their translating into control commands for external devices.

In this research, we perform recurrence quantification analysis (RQA) of multichannel human electroencephalogram (EEG) during motor action on command. In course of the study, RQA appears to be a relevant mathematical approach for detection of transitions in nonstationary biological time series. Application of RQA allows to provide insight into properties of motor-related activity in human brain, particularly to describe features of movement planning and execution.

It is known that motor-related EEG activity is associated with suppression of $\mu-$band oscillations ($8-13$ Hz) in somatosensory area of brain cortex. We used this feature of brain activity to distinct different stages of motor action from EEG recordings and reveal underlying neural dynamics. Thus, we applied RQA not to raw EEG data but to the time series of $\mu-$rhythm dynamics obtained via wavelet transform. As the main characteristic we used RQA measure of determinism (DET), that reflects regularity of considered process. We observed significant decrease of DET in cerebral cortex channels (C3 and C4) for right hand and left hands movement execution. We also obtained significant changes in DET values in occipital and frontal areas in the moment between signal and movement onset. We imply that such dynamics is associated with motor preparation.

We suppose that our findings will be helpful for the development of brain-computer interfaces (BCIs) directed at assisting or improving motor functions.

Reliability of Recurrence Network Analysis against the observability properties of the recorded time series *Poster*

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Both recurrence quantification analysis (RQA) and recurrence network analysis (RNA) are remarkable techniques for the detection of dynamical transitions in experimental applications. In practice, often only one single scalar time series is recorded in an experimental scenario, and a state-space reconstruction is required prior to the application of RQA or RNA. An established fact from embedding and observability theories is that the reconstruction "quality" is hampered if the recorded variable conveys poor dynamical information of the system's states (i.e., conveys poor observability). Hence, the application

of RQA and RNA on a *low quality* reconstruction could lead to it misleading results. This was already investigated in the context of the former, but for the latter the consequences are still unknown. The aim of this work is to investigate the RNA robustness against the observability properties of the recorded time series. To this end, numerical investigations are performed using two benchmark systems: the autonomous R"ossler system and the non-autonomous Duffing-Ueda oscillator. RNA is conducted on each system's state variable using a 2-dimensional parameter grid. In this case, we are mainly interested in the detection of *shrimp* structures, that is, *islands of periodic behaviour* surrounded by large regions of *chaotic sea*. Thus, the results obtained from (the embedding of) each state variable are compared with: (i) the maximum Lyapunov exponent ($\lambda_{\max}$), and (ii) the results from the direct application of RNA on the original state-space (i.e., with no embedding). Two statistical analysis methods are applied in order to compare the performance of RNA metrics with respect to the observability properties: the area under the curve (AUC) of the Receiver Operating Characteristics (ROC), and the Mutual Information (MI). The results show that the characterization of shrimp structures by using variables of *good* observability is quite similar to the application of RNA directly on the original state-space $\vec{x}$. On the other hand, variables of *poor* observability heavily impair the state-space reconstruction and, consequently, the RNA measures, with the exception of the clustering coefficient $\mathcal{C}$. This measure robustness to observability issues, together with its proficiency to detect dynamical transitions, highlights it as a valuable choice for RNA applications – specially when no prior information of the variable observability is available.

Investigation of chaos-periodicity transitions in the Duffing system by recurrence analysis

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The Duffing system with a double-well potential describes many mechanical and physical oscillators. For this reason, it is widely and extensively studied mathematically and numerically.

In this work we join this trend, and use the RP technique to analyze in detail changes in the dynamics of the Duffing system which occur as a result of changes in its damping.

The bifurcation diagram calculated for a wide range of damping decrement shows chaotic solutions with many regular windows. This work focuses on studying selected chaotic fragments and some regular windows. By comparing the bifurcation results and RQA (Recurrence Quantifiers Analysis) variables, the system dynamics is thoroughly examined in the considered ranges of variation of the damping parameter.

By using appropriate optimization of RP method parameters and supporting the analysis with results obtained with other methods such as phase diagrams, FFT spectra and Lyapunov exponents, it is proved that recursive variables can detect very subtle differences in the dynamics of the studied system.

Analysis of Thermoacoustic Systems using Recurrence Plots

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Thermoacoustic instability refers to the ruinously large-amplitude acoustic oscillations that are established inside a combustor when the unsteady heat release rate from the combustor has a positive feedback with the acoustic perturbations. These oscillations often have catastrophic consequences, leading to failure of systems such as gas turbine engines and rockets. We use recurrence based methods to identify and characterize thermoacoustic transitions. Recurrence plots were used to characterize intermittency which was observed prior to onset of thermoacoustic instability and flame blowout. Early warning signals of impending thermoacoustic instability and blowout were obtained using recurrence quantification analysis. We further used recurrence networks to characterize the dynamical states and the transitions between these states. We used measures derived from recurrence plots and recurrence networks to characterize the synchronization transition observed during the onset of thermoacoustic instability, and the directional dependence between the acoustic field and the heat release rate fluctuations.

Nonlinear analysis of the helicopter main gear transmission vibrations using recurrences

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In our work, we have analyzed the non-linear vibrations of the main helicopter transmission registered on an experimental measuring stand. By means of two three-

axis vibration sensors placed in different areas of the helicopter's main gearbox housing, the acceleration vibrations were recorded for two cases: a gearbox that failed the efficiency test and the transmission, which was then replaced with a new one after this test. The vibration analysis of the helicopter main transmission is complicated due to its construction, where the first stage is an angle gear and the other is planetary gears with several satellites. This causes the sidebands to occur around the frequency of the characteristic elements of the drive system and increase the complexity of the signal. In earlier studies, we demonstrated the usefulness of the recurrence method to distinguish between a damaged gear and a non-defective transmission in the case of the final drive. Therefore, we will use the CRQA indicators, investigating the non-linear relationships between the two systems: before replacing the transmission and after replacing it with a new one. Due to the aforementioned complexity of the transmission process of the main transmission drive, we made the empirical mode decomposition of signals into experimental modes (EEMD), which were then used as a non-linear correlation analysis by means of CRQA indicators. We assumed that the occurrence of damage will cause an increase in non-linearity in the system, which will be reflected in the values of CRQA measures for a given mode. In turn, each mode can be treated as a component of the signal at a specific frequency which can be helpful in determining the location and type of transmission damage.

Analysis of the recurrence properties of the combustion fluctuations in a lean-burn SI natural gas engine

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In this paper, the cycle-to-cycle variations (CCVs) in combustion process in a spark-ignition (SI) natural gas engine were investigated under a lean burn condition. The dynamics of the indicated mean effective pressure (IMEP) fluctuations were examined. The engine was operated at 800 rpm and an engine load of 25%, and a lean mixture with excess air coefficient of 1.6 was used. The spark advanced angle (SAA) was changed from 20 to 30, 35, 40, and 50°CA BTDC. For each SAA, the dynamics of combustion system was analyzed by means of recurrence-time statistics. The probability densities of the mean recurrence time (MRT) and the finite-time Lyapunov exponents (FTLEs) were calculated. The results show that SAA has a significant effect on the dynamical characteristics of combustion system in a natural gas engine. For the SAA of 30 and 35°CA BTDC, the distributions of MRTs display Gaussian shapes and are found to be in agreement with those of the FTLEs. However, the distributions of MRTs show asymmetric and possess exponential tails for the SAA of 20, 40 and 50°CA BTDC. Our results may be useful for understanding the complex internal nature of the combustion fluctuations. They can also be used to develop more sophisticated control strategies for improving the combustion stabilities of lean-burn natural gas engines.

A Language Paradigm for Unifying Recurrence Plots and Quantifications Across Disciplines

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Recurrence plots were first introduced in the context of the Hénon map (1987) and Lorentz equations (1992). But early on it became apparent that physiological processes like breathing (1994) and fatiguing muscles (1995) were amenable to this new methodology on living, dynamical systems. As the years have passed recurrence plots and their quantifications have found utility for diagnosing various systems over multiple disciplines. Why might this be the case? We posit that the popularity and success of recurrence analyses across disciplines are attributable to the common denominator of dynamical motions being present in everything. Animate and inanimate systems both "wiggle" in time and/or space. Parallel to the mathematical world of scalars and vectors, the paradigm of language becomes an intuitive and useful tool for explaining recurrences in terms of categorical letters and words.

In this study we demonstrate how systems "speak" and produce language as it were. Any detected changes in the "speech" reveal system states changes, some of which may be pathologic or disintegrating. Numeric data from many example systems were partitioned into 26 bins corresponding to the 26 letters in the English alphabet. Bin counts were rank-ordered and paired with decrementing letter frequencies statistically derived from almost 744 billion recurring English words (about 98 thousand distinct words) in the Google books Ngrams data base. The output stream of letters was interrupted with spaces to form (unintelligible) "words" according to the asymmetric (right-skewed) distribution of regular English word lengths (1 to 12 letters long). Information in these linguistic structures were studied by recurrence plots and recurrence quantifications at the orthographic and word levels (RADIUS = 0; EMBED = 1 to 20). For most systems, save random ones, shuffling of the native sequences destroyed the inherent information content of the original data (de-

creased DETERM). Two pedagogical lessons stand out from this work: 1) most dynamical systems "speak" with meaningful contents that point to underlying deterministic rules; and 2) recurrence quantification analysis is a powerful linguistic tool irrespective of the scientific discipline employing it.

Effect of oxygenated fuels on the dynamics of combustion instabilities in a common-rail diesel engine

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This paper investigates the effect of oxygenated fuel additions on the dynamics of combustion instabilities in a high-pressure common-rail diesel engine. As an oxygenated additiveÃŕÅŠÂŇ4% and 8% (by volume) of triacetin were added to waste cooking biodiesel to change the oxygen content in biodiesel. Oxygen ratio was changed from 10.93 to 12.25 and 13.57%. Engine was operated at speed of 1685rpm and engine load of 25%. The dynamics of the indicated mean effective pressure (IMEP) fluctuations were examined by calculating recurrence plot (RP) and recurrence qualification analysis (RQA).The results show that with the increase of oxygen contents, the cyclic combustion stabilities at low engine load are improved, and the RQA measures(determinism (DET), Entropy(ENTR) and Laminarity (LAM)) systematically decrease.

Bridge Damage Detection under Moving Loads Based on Multi-Sensor Recurrence Plots

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Recurrence plot is an effective tool to analyze the dynamics of complex systems. Here, a novel signal-based damage detection approach for bridge structures under moving loads using the recurrence quantification analysis measures is proposed. Firstly, the theoretical basis of damaged bridge structure vibration under moving load is presented. The recurrence plots of structural responses are formed considering multi-sensors, e.g., sensors at different locations, different types of sensors and so on. Then the corresponding recurrence quantification analysis is carried out, a damage-sensitive measure is proposed by moving window-based local recurrence rate to identify and locate the damages. Finally, numerical studies on a simply supported beam are conducted to investigate the sensitivity and robustness of the proposed approach for accurately identifying bridge damage.

Heterogeneous recurrence analysis

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Process monitoring of dynamic transitions in complex systems (e.g., disease conditions or manufacturing quality) is more concerned about aperiodic recurrences and heterogeneous recurrence variations. However, little has been done to investigate heterogeneous recurrence variations and link with the objectives of process monitoring and anomaly detection. This talk will present the state of art in nonlinear recurrence analysis and a new heterogeneous recurrence methodology for monitoring and control of nonlinear stochastic processes. Specifically, the developed methodologies will be demonstrated in both manufacturing and healthcare applications.

Graphlet based time series analysis: A kinetic theory for Complex systems

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A complex system contains many elements that are networked by the relationships between them. A quantitative description of the system's state and its evolutionary behaviors can shed light on the underlying dynamical mechanism, be helpful in evaluation, prediction and regulation. The dynamical process of the system produces a mono/multi-variate time series. There exist generally non-trivial patterns in the series. And the patterns are inter-dependent, rather than isolated. If we regard the patterns as nodes and their dependencies linkages, the time series is mapped to a complex network.

In our approach, from the time series we extract all the possible segments with a specified length. The segments are then mapped to graphlets to represent the state of the system in the corresponding duration. The time series is then converted to a chain of unique graphlets, which is taken as the trajectory of the system. The transition matrix for the unique graphlets provides us the evolutionary behaviors of the system. In this talk, we will present

our effort in this topic, including the graphlet based analysis of time series for deterministic and stochastic dynamical processes, the multi-scale graphlet based approach to complex dynamical processes, and the application to empirical data from stock markets and physiological systems.

It is found that the graphlet based approach can display new structural properties that are stored in time series but merged by the statistical procedure in traditional series analysis methods. Taking the graphlet as representative of state, one can reach an effective evaluation of the complex system, and extract reliable early-warning signals of crises. What is more, the transition matrix provides a unified framework to understand the statistical and structural properties of time series.

Quadrant scan for multiple scale transition detection

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Transition detection in temporal and non-temporal signals is a problem encountered in various disciplines. We investigate the developed Quadrant Scan technique to analyse recurrence plots to identify tipping points of a system. We define two types of transition and prove analytically the ability of Quadrant Scans to detect both types, we then provide an extension by considering a weighting scheme. We further highlight the merits of Quadrant Scan and our extension by studying several applications. The ability of Quadrant Scan and its extension to deal with non-temporal, multivariate or large data sets and their capability to classify multi-scale transitions are investigated in detail.

Static Balance and Control Strategy in Children Aged 3 to 6 Years

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Abstract Objective The present study aimed to investigate the age-related differences of static balance and control strategy in preschool children aged 3 to 6 years in simple sensory conditions. Mehods Using 2×3(vision×age) two-factor experimental design, 105 preschool children, between 3 and 6 years of age, participated in this study. Postural balance was measured for 15s in two conditions (eye open/eye closed on stable ground) by using AMTI platform. The traditional measures of center of pressure (mean sway velocity in antero-posterior and medio-lateral direction) were calculated as the parameters of static balance, the non-linear analysis of center of pressure (recurrence quantification analysis, RQA) were calculated as parameters of control strategy. Result (1). mean sway velocity ($p < 0.05$) in medio-lateral direction and mean sway velocity ($p < 0.01$) in antero-posterior direction of COP significantly decreased with the age increases; (2). %DET($p < 0.01$) in the medio-lateral direction of COP showed significantly different with the age increases; (3). %DET in the medio-lateral direction of COP showed an increasing trend in EO (eye open) condition and a decreasing trend in EC (eye closed) condition. Conclusion The preschool children show a non-linear improvement trend with age, especially the static balance of preschool children aged 5–6 years is significantly better than that of preschool children aged 3–4 years and 4–5 years. Role of vision is very important to preschool children, especially for children aged 3–4 years. Compared to the preschool children aged 3–4years, the balance control of preschool children aged 4–5 has changed obviously.

xRQA for head nodding mimicry behaviour analysis in a VR monologue interaction

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Previous research ("Digital Chameleons") suggested that a virtual speaker (agent) automatically mimic listener's head nodding behaviour is more persuasive. With a specially constructed virtual environment and full body mocap system, we tested the agent's persuasiveness by manipulating its behaviour in three conditions 1) Mimic – the agent mimics a participant's head movements at a 4s delay. 2) Playback – the agent replays the previous participant's head movements. 3) Original – the agent replays the original speaker's movements. The results provide no evidence of differences in participant's subjective estimates of: a) social presence b) agreement with the agent c) general impression of the agent in the three different conditions which do not support the original finding of differences in ratings of agent persuasiveness between conditions. They also provide no evidence of differences between conditions in participant's overall responsiveness, as indicated by gross measures of their concurrent head movements. However, with Cross Recurrence Quantification Analysis, we found that the (original) human speakers move much more than their chameleon or nodding dog counterparts and that listener also repeat the human speaker's movements systematically less than the chameleon (trivially) or nodding dog (non-trivially). We argue that a key weakness of this paradigm in its current

form is the failure to properly address the reciprocal dynamics of natural non-verbal interaction: speakers and listeners in ordinary conversation interact incrementally and selectively to arrive at a joint understanding. The automatic mimicry model is too simplistic and that this paradigm must address the reciprocal dynamics of non-verbal interaction to achieve its full potential.

Analyzing long-term correlated stochastic processes by means of recurrence networks: Potentials and pitfalls

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Over the last ten years, complex network representations have been proposed to characterize statistical properties of the underlying system associated with its geometry in phase space. In particular, recurrence network approaches have found various applications in different discipline. When constructing a recurrence network (RN) representation for time series, the vertices of the network are given by the individual state vectors sampled from a given trajectory, whereas network connectivity is established according to their mutual closeness in phase space. In order to obtain reliable results, we have to consider the impact of several algorithmic parameters such as recurrence threshold, embedding parameters, sampling rate, or even the selection of variables in multi-dimensional systems, which has been extensively discussed in previous works. In this talk, we will highlight the potentials and conceptual as well as practical limitations when applying the RNs to fractional Brownian motion and related stochastic processes. Complementarily, we analyze some RN properties of the closely related stationary fractional Gaussian noise (fGn) processes and find that the resulting network properties are well-defined and behave as one would expect from basic conceptual considerations. Our results demonstrate that RN analysis can indeed provide meaningful results for stationary stochastic processes, given a proper selection of its intrinsic methodological parameters, whereas it is prone to fail to uniquely retrieve RN properties for non-stationary stochastic processes like fBm. In the last, we will show that the RN analysis can discriminate chaos in Hamiltonian systems.