Scientific and Organisational Committee

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Aims

The objective of this recurrence symposium is to encourage the exchange of knowledge among scientists working in the disciplines of time and spatial series analyses. Recurrence plots and recurrence quantifications are general methods for visualising and analysing both linear and nonlinear time series data. We continue to witness many new technical developments related to recurrence plots. Some of these include: a framework to treat recurrence plots as a network from which one can obtain network-related statistics; inferring directional couplings; identifying deterministic chaos; obtaining confidence intervals for recurrence quantification analysis; defining recurrence plots for point processes. In addition, applications of recurrence plots are increasing in areas such as mathematics, neuroscience, physiology, psychology, weather and climate, financial systems, and linguistics. This symposium will provide a unique forum to help combine the recent theoretical developments in recurrence science with applications from various fields. The submitted theoretical and applied contributions promise a very exciting symposium in Hong Kong. We hope everybody will enjoy the meeting and find new inspirations and cooperations.

Location

The symposium will be held at the the Hong Kong Polytechnic University. The university is in the Hung Hom district within walking distance of Tsim Sha Tsui and adjacent to the Hung Hom MTR station (and at the terminus of the Hong Kong-Canton express trains service to Guangdong).

Registration reception

A registration reception will be held starting at the podium level of the university near A-core (and subsequently in AG712) Sunday 18:00–21:00h. Beer, soft drinks, and nibbles will be available.

Lectures

The symposium will take place on the seventh floor of the ”Chung Sze Yuen Building”, entrance via the lift well marked at location A (the entrance itself is marked with a large capital ”A”). The lecture room is AG710. Posters and discussion will be in room AG712 (adjacent

rooms). Coffee and tea will be served outside AG710 (attendees can also inspect posters during that time).

Practical Workshop

In the symposium, several approaches of analysing recurrences can be practically applied to own data under supervision. Instructive presentations introduce in the *RQA software*, *CRP toolbox* and further software for recurrence analysis. A comprehensive RQA, study of interrelations, synchronisations or dynamical invariants can be provided.

The practical workshop will take place in the computer lab CF504 at the Hong Kong Polytechnic University. Note that it is at a different part of the campus (see map).

Lunch

Monday, Tuesday and Wednesday lunch: Chinese style lunch included. Staff restaurant, 4th floor, communal building. Guides will be provided from the conference venue.

Social Event

Tuesday

On Tuesday, December 6th, we plan to have a dinner/banquet. Let us know during registration whether you would like to join. A contribution to cover the costs will be requested during registration.

Wednesday

Moreover, an excursion has been organised for Wednesday afternoon, December 7th, to Victoria Peak on Hong Kong Island. Buses will depart from the "Logo Square" (on the ground floor outside A-core) at 15:30. The return buses will leave Victoria Peak shopping area at 18:30 – sharp. Once we get to the Peak there are no organised activities, you are free to do whatever you want: enjoy the food, the view, shopping, or go for a walk.

There are two multistory buildings in the general vicinity. The front one, which was built more recently, and much to the consternation of the owners of the rearward tower, is The Peak Tower – it's the one shaped like a giant flattened wok. The rear building is slightly less ostentatious and this is The Peak Galleria. Both buildings are packed with shops, bars and restaurants. The Peak Lookout restaurant (across the road from both towers) is slightly less busy and also recommended. To get the best views, head to the top of the Peak Tower (they do charge for the very best bits though). If you prefer not to pay to look at the skyline, the roof of the Peak Galleria is also publicly accessible and offers almost equal views – with the added bonus that you can also look to the South over the South China Sea. If you prefer to take a hike, follow Lugard and Harlech Roads for an approximately one hour circuit of the actual Victoria Peak (this route is flat and easy and offers good views of all sides), or climb Mount Austin Road to Victoria Peak itself (about half an hour – not so flat): see .

If you wish to catch the tour bus back to the Hong Kong Polytechnic University campus at 18:30 you must be punctual – it is not possible for tour buses to wait at this location for stragglers. If you do miss the return bus or choose not to take it, then that is not a problem. There

are many transport options from Victoria Peak, including:

- The peak tram: departing from the peak tower, single tickets $28. Once in Central (i.e. the city), the lower terminus of the tram is at Garden Road. From there it is a short walk downhill to central business district (and the bars and restaurants of Lang Kwai Fong), or you can catch the 15C bus (an open-top double decker). The tram and the open-top bus are tourist attraction in their own right – but there can be queues from the peak. See .
- By bus: there is a bus terminus at the Peak (under the Peak Galleria). Route 15 goes to Central and then to the Ferry Piers. Route 15B goes to Causeway Bay and more shops and more crowds. Both cost a little less than $10. In either case, the best seats for the return journey are up the front on the top deck – so long as you're not prone to motion sickness.
- By minibus: also departing from the same bus terminus, green-top minibuses (seating about 15-20 people) depart for Central (IFC building) and cost approximately $8. When you want to get off, just press the button (if such is fitted), or if not just yell out to the driver – try to copy what everyone else does. Minibuses are permitted to pick-up and drop-off passengers anywhere — so when you tell the drive to stop, he stops.
- By Taxi: Taxis can be hailed anywhere (where vehicles are permitted to stop), there is a Taxi stand in the bus terminus under the Peak Galleria. Taxi drivers might be a bit grumpy about crossing the harbour though – they tend to prefer to stick to one side or the other (by law they should take you and they are permitted to charge a small premium for cross harbour trips, but they may simply plead ignorance of your intended destination). Special cross-harbour taxi ranks are for taxis that want to cross the harbour (and don't charge such a premium for the journey) — these are sign-posted.
- By Foot: It'll take a couple of hours but it's all downhill. There are several possible routes, either you can veer off from Harlech Road at the children's playground and BBQ area: just head downhill (it's sign posted) and then simply keep going down: eventually you'll end up on Conduit Road from where you can keep walking down, or catch the number 3 mini-bus. Alternatively, follow Old Peak Road down from the Peak Tower: this is a somewhat more direct (and steeper) route - you'll wend your way between large apartment blocks, a small zoo, bypassing the (former) governor's residence, and finish up somewhere in Central.

Once you do get back to the city, if you are heading to the university, you still need to cross the harbour. Either go to the central ferry pier (Pier 7) and catch the star ferry to Tsim Sha Tsui (another Tourist must-see and probably one of the worlds cheapest harbour cruises — it costs $2-$3 depending on when you go and where you sit). From Tsim Sha Tsui you can either walk along the water front (past what the HK Tourist Authority refers to as the "Avenue of Stars" — a tacky eastern version of the Hollywood Walk of Fame, but a nice waterfront promenade, nonetheless) back to the campus or catch the number 5 bus. If you don't wish to catch the ferry, the alternative is the ubiquitous MTR to Hung Hom station — or any bus (numbered 100-119) heading to the cross harbour tunnel: get off immediately after the tunnel.

Internet Access

Campus WiFi will allow institutional users access via eduroam: log-in with credentials provided by your home institution.

Alternative WiFi for symposium participants with the following login details:

SSID: `RecurrencePlots`
Username: `Poincare`
Password: `Eckmann87`

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 35 min, plus 10 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

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.

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.

Programme

Monday, December 5th

8:30 Registration

Introduction

9:00 Opening

9:05 **Norbert Marwan**:
Introduction Lecture Recent achievements in recurrence plot research

Methodological Aspects

9:30 **Diogo C. Soriano**:
Keynote Lecture Blind source separation and extraction using recurrence

10:15 Zahra Aryani, **Behzad Babaei**:
On the selection of radius threshold in recurrence quantification analysis

10:35 *Coffee break*

11:00 **Vladislav B. Kiselev**, Boris V. Kiselev:
Studying asymmetry in complex systems without using CRPs

11:20 **Ricardo A. Rios**, Rodrigo Fernandes de Mello:
Time series decomposition in terms of stochastic and deterministic components: an approach using recurrence plot and empirical mode decomposition

11:40 **Dilip K. Bhattacharya**, Sayan Mukherjee:
Fuzzy recurrence plot and its application in phase space analysis

12:00 **Sayan Mukherjee**, Sanjay Kumar Palit, Dilip K. Bhattacharya:
Application of recurrence plot to verify Taken's theorem in some dynamical systems

12:20 Thiago de Lima Prado, Paulo Paneque Galuzio, Ricardo Luiz Viana, **Sergio Roberto Lopes**:
Image processing using recurrence plots

12:40 **Jie Zhang**:
Multiscale recurrence plot

13:00 **Michael Small**:
Welcome note

13:10 *Lunch*

14:00 **Michael Small**:
Recurrence networks for discrete data

14:20 **Iliusi Vega**:
Method for tuning the threshold for recurrence plots and its efficiency in recognizing different dynamical states through recurrence network analysis

14:40 Jan H. Feldhoff, **Reik V. Donner**, Jonathan F. Donges, Norbert Marwan, Jürgen Kurths:
On bi- and multivariate extensions of recurrence network analysis

15:00 **Ruoxi Xiang**, Xiaoke Xu, Michael Small:
Drawing links between time series and complex networks – Multiscale characterization on recurrence-based phase space networks constructed from time series

15:20 **Yong Zou**:
Are recurrence networks scale free?

15:40 *Coffee break*

16:15 **David M. Walker**, A. Tordesillas, A. Rechenmacher, S. Abedi:
Connecting the dots in networks of grain kinematics

Applications in Biological Systems I

16:35 **Charles L. Webber, Jr.**:
Assessing coupling strength between discrete events using cross recurrence quantifications

16:55 **Christian Heinze**, Udo Trutschel, David Sommer, Martin Golz:
Application of Recurrence Plots to long-term heart rate recordings for the analysis of circadian rhythmicity

Tuesday, December 6th

8:50 Welcome & miscellanous announcements

Applications in Biological Systems II

9:00 **Philippe Faure**:
Keynote Lecture Recurrence plot analysis of symbolic sequence. Application to behavioral data

9:45 **Daniel Angus**, Andrew Smith, Janet Wiles:
Conceptual recurrence plots: Generating insights into effective doctor-patient consultations

10:00 **Saritha Namboodiri**, Chandra Verma, Pawan K. Dhar, Alessandro Giuliani, Achuthsankar S. Nair:
Sequence signatures of allosteric proteins towards rational design

10:20 **Sonja Hermann**, Dermot Power, Richard Reilly:
RQA – a means of predicting pressure relief movements in the prevention of pressure ulcers?

10:40 *Coffee break*

11:15 **Xiang Li**:
Analyses of electrocardiograph with the eyes of complex network theory: a snapshot

11:35 **Dean Korosak**, Andraž Stožer, Jurij Dolenšek, Marko Gosak, Marko Marhl, Kousuke Yakubo, Marjan S. Rupnik:
Recurrence, visibility and correlation networks of calcium dynamics in pancreatic islets

11:55 **Ralf F. A. Cox**, Bianca Huurneman, F. Nienke Boonstra:
Temporal structure in the eye movements of 6- to 8-year-olds during crowded visual search

12:15 *Lunch*

Workshop

14:00 **Practical Tutorials**
CRP Toolbox for Matlab, RQA Software

19:30 *Social Event*

Wednesday, December 7th

8:50 Welcome & miscellanous announcements

Applications in Engineering

9:00 **Maryam Tahmasebpour**, Reza Zarghami, R. Sotudeh-Gharebagh, N. Mostoufi:
Characterization of gas-solid fluidized bed hydrodynamics by recurrence plot analysis

9:20 **Dong Yang**, Wei-Xin Ren:
Recurrence quantification analysis based operative nonstationarity assessment for structural ambient vibration signals

9:40 **Mohammad Ali Sanjari**:
Reliability of Recurrence Quantification Analysis Measures of Hand Drawings

10:00 *Coffee break*

Further directions

10:45 **John Delos**:
Keynote Lecture Recurrence spectroscopy: Classical orbits and quantum spectra

11:30 **P. Bagavathi Sivakumar**, V. P. Mohandas:
Recurrence plot and recurrence quantification analysis as a tool for determining determinism in time series data: An empirical study on Indian stock data

11:10 Poster Session

13:00 *Lunch*

Applications in Earth and Astrophysical Sciences

14:00 **Yoshito Hirata**, Kazuyuki Aihara:
Recurrence plots for point processes and their application to earthquakes

14:20 **Alexander V. Glushkov**, Olga Yu. Khetselius, Georgy P. Prepelitsa:
Studying and forecasting the atmospheric pollutants dynamics by using the non-linear prediction approach and recurrence plots method

14:40 **Holger Lange**:
Using recurrence quantification analysis for a detailed model-data comparison: the case of a water transport model

15:00 Closing

16:00 *Excursion*

Poster

Methodological Aspects

Poster 1 **Zahra Aryani**:
Optimum Selection of Minimal Length of Line in Recurrence Quantification Analysis

Poster 2 **Vladislav B. Kiselev**:
Window Size Problem in Recurrence Quantification Analysis

Poster 3 **Eulalie Joelle Ngamga**, Norbert Marwan, Jonathan F. Donges, Jürgen Kurths:
Network approach for unvealing subtle transitions in dynamical systems

Poster 4 **Aloys Sipers**, Paul Borm, Ralf Peeters:
On the reconstruction of a signal from its unthresholded recurrence plot subject to disturbances

Applications in Engineering

Poster 5 **Behzad Babaei**, R. Zarghami, R. Sotudeh-Gharebagh:
Identification of Change in Particles Size in Fluidized Beds Using Recurrence Quantification Analysis

Poster 6 **Alexander V. Glushkov**, Viktor M. Kuzakon, Georgy P. Prepelitsa, Elena P. Solyanikova:
Studying interaction dynamics of the non-linear vibrational systems on the basis non-linear prediction approach and recurrence plots method (application to semiconductor quantum autogenerators)

Poster 7 **Han Xiao**, Yourong Li, Lv Yong:
The Gear's Fault Recognition Based on Recurrence Quantification Analysis and Gaussian Mixture Model

Poster 8 **Washington C. de A. Costa**, Silvana C. Costa, Vinícius J. D. Vieira, Benedito G. Aguiar Neto e F. M. de Assis:
Recurrence Quantification Analysis Applied to Pathological Voice Discrimination

Applications in Earth Sciences

Poster 9 **Ondřej Kopáček**, Jiří Kovář, Vladimír Karas, Zdeněk Stuchlík:
Recurrence analysis and chaotic motion around Kerr black hole

Applications in Biological Systems

Poster 10 **Shu Dai**, James Keener:
Use noise to determine cardiac restitution with memory

Poster 11 **Deshpande Rangaprakash**:
Recurrence Quantification Analysis of Electroencephalogram and Heart Rate Variability data with applications

Poster 12 **Ashish Kaul Sahib**, N. Pradhan:
Understanding coupling and synchronization in EEG of epileptic discharge using recurrence analysis

Poster 13 **Deshpande Narayana Dutt**, B. S. Raghavendra:
Application of Recurrence Quantification Analysis for the Study of Altered States of Consciousness

Poster 14 **Junfeng Sun**, Jijun Wang, Shanbao Tong:
Joint recurrence analysis on EEG signals of schizophrenia patiens in multiple frequency bands

Applications in Finance and Economics

Poster 15 **Marieke van Rooij**:
Recurrence patterns in risky decisions

Abstracts

Conceptual Recurrence Plots: Generating Insights into Effective Doctor-Patient Consultations

Daniel Angus, Andrew Smith, Janet Wiles

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Effective communication between healthcare professionals and patients is critical to patient health outcomes. The doctor/patient dialogue has been extensively researched from different theoretical perspectives, with findings emphasising a range of communication behaviour that leads to effective communication. What is often unclear is how engagement occurring throughout the whole consultation in a doctor/patient dialogue relates to the effectiveness of the consultation. To investigate this issue we applied a recurrence plotting technique to analyse examples of training and clinical medical discourse transcripts. This conceptual recurrence plotting technique automatically builds an internal language model from an unmarked conversation transcript, tags conversation turns based on their conceptual content, and generates an interactive recurrence plot of the discourse under study. The analysis afforded by the conceptual recurrence plotting technique is useful in examining whole consultation scale interactions, and findings from this work are helping to highlight effective consultation techniques including accommodative, engagement and repetition behaviours.

On the Selection of Radius Threshold in Recurrence Quantification Analysis

Zahra Ariani, Behzad Babaei

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A new strategy was developed to prepare the optimum value of radius threshold, the crucial parameter in recurrence quantification analysis. An index is defined as dynamic characteristic of the system. The value of radius threshold which maximizes the index is selected as optimum value. Using this strategy, all of the dynamic features of the underlying system is revealed. The strategy is very useful in monitoring of dynamic systems and analysis of experimental data.

Optimum Selection of Minimal Length of Line in Recurrence Quantification Analysis *Poster*

Zahra Aryani

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A method for optimum selection of minimal length of line (lmin) is defined for application in recurrence quantification analysis.This value of lmin can clearly exhibit details of the dynamic of underlying system. A simple linear model was developed. This model relates lmin to average diagonal line of the global dynamic. Coefficient of the model was calculated for three well-known systems. The result showed that coefficient k does not depend on epoch length and radius threshold for a specific system.

Identification of Change in Particles Size in Fluidized Beds Using Recurrence Quantification Analysis *Poster*

B. Babaei, R. Zarghami, R. Sotudeh-Gharebagh

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Recurrence quantification analysis (RQA) of pressure fluctuations was used to identify the addition of coarse particles into the gas-solid fluidized bed. The analysis showed that RQA is able to detect steady state effects of coarse particles on the bed hydrodynamic even if gas velocity is fluctuated slightly. Since gas velocity cannot be exactly fixed in industrial applications, this result can be applied to industrial fluidized beds for agglomeration detection. This method is simple, robust, and reliable which can be applied to short term data (well for on-line monitoring) as well as long term data.

Recurrence Plot and Recurrence Quantification Analysis as a tool for determining determinism in time series data: An empirical study on Indian Stock Data.

P. Bagavathi Sivakumar, Dr. V. P. Mohandas

Amrita VishwaVidyapeetham - UNIVERSITY, Computer Science and Enginnering, Coimbatore, IN
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Recurrence plots have been widely used in various domains. Recurrence Plots (RPs) were first described by J.P. Eckmann, S. O. Kamphorst and D.Ruelle. RP is a relatively

new technique for the qualitative assessment of time series. With RP, one can graphically detect hidden patterns and structural changes in data or see similarities in patterns across the time series under study. Financial time series data used in this study is closing stock prices of various indices of National Stock Exchange (NSE) of India. (Source: www.nseindia.com). Totally ten such indices, namely, S&P CNX NIFTY, BANK NIFTY, CNX 100, CNX INFRASTRUCTURE, CNX IT, CNX MIDCAP, CNX NIFTY JUNIOR, CNX REALTY, S&P CNX 500 and S& PCNX DEFTY were used. For the state space reconstruction, Average Mutual Information (AMI) was found and the corresponding time lag or time delay was obtained. Using the method of false nearest neighbors, minimum embedding dimension was found. Then recurrence plots were drawn for all the series and inferences were made for Stationarity, Non stationarity, periodic, random and deterministic patterns. To analyze further, the following information were found or computed: Spatio-Temporal Entropy, Recurrence histogram, Hurst Exponent, %REC, %DET, MAXLINE, TREND, ENT, %Laminarity, Trapping time, and Ratio. For the ten time series under investigation the average values obtained were as follows: %DET = 20% and STE = 25%. Thus the study shows the presence of both deterministic and stochastic components and roughly there is 25% of determinism.

Fuzzy recurrence plot and its application in phase space analysis

Dilip K. Bhattacharya, Sayan Mukherjee

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The paper introduces the notion of fuzzy recurrence plot (FRP) as a modification of standard recurrence plot (RP). With the help of a suitable fuzzy function, first of all, recurrent and non-recurrent points of the phase space trajectory of the dynamical system are completely separated in R3. Next the recurrent points are themselves grouped into three classes, most recurrent, almost recurrent and at most recurrent. The classified recurrent points are represented in R3 in three regions separated by three planes parallel to xy-plane. Thus, the recurrence is explained linguistically with suitable phrases. Further, the notions of vertical and diagonal lines are introduced, their finer interpretations for points on the trajectory are discussed with special reference to a Ecological dynamical system.

Recurrence Quantification Analysis Applied to Pathological Voice Discrimination *Poster*

Washington C. de A. Costa, Silvana C. Costa, Vincius J. D. Vieira, Benedito G. Aguiar Neto e F. M. de Assis

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This work investigates the potential of recurrence quantification measures to discriminate healthy voices and voices affected by different types of laryngeal pathologies. Traditional clinical tests to detect laryngeal pathologies are generally considered to be invasive, causing discomfort to the patient. Acoustic analysis appears as an auxiliary, noninvasive, low cost and easily implemented tool to monitoring surgical and pharmacological treatment, as well as pre- and post-diagnosis of vocal fold pathologies. Most of speech production models make the assumption that it has been generated from a time-varying linear system. In recent years researchers have tried to obtain a model capable of incorporating the nonlinearities inherent in the human voice production system. Another factor that prompts the search for new techniques for analyzing the voice signal is its nonstationarity in the long time interval. The speech signals are selected from the Kay Elemetrics Database, Model 4337, containing sustained vowel /ah/ of 53 signals of healthy voices and 100 pathological voices (55 with paralysis and 45 affected by vocal fold edema). The Visual Recurrence Analysis 4.9 Software (by Eugene Kononov) and the package routines RQA 1.13 (by Charles Webber Jr.) are used to obtain the parameters of embedding and recurrence quantification measures, respectively. In order to get the recurrence matrix for each signal, the largest value of the radius that keeps the recurrence rate less than or equal to a certain threshold is chosen. Five different thresholds are considered at recurrence rate: 5%, 4%, 3%, 2% and 1%. We analyzed the behavior of recurrence quantification measures: determinism, entropy, the maximum length of the diagonal lines, laminarity, maximum length of vertical lines and trapping time. Hypothesis tests applied has revealed significant statistical differences between the groups of healthy voices and pathological voices for all measures evaluated. Some of the measures assessed presented statistically significant differences between the two different groups of pathological voices. The individual performance of each measure to quantify the task of discriminating between groups of healthy and pathological voices was made by discriminant analysis using the Mahalanobis distance measure. A correct classification of 92.86 % was obtained. On the other hand, the combination of the measures, two-by-two, gave better results (94.64%) to discriminate between the two groups by diagquadratic discriminant analysis. These results suggest that the recur-

rence quantification measures offer an effective potential in discriminating between healthy and pathological voices affected by paralysis and vocal fold edema.

Temporal structure in the eye movements of 6- to 8-year-olds during crowded visual search *Poster*

Ralf F. A. Cox, Bianca Huurneman, F. Nienke Boonstra

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It is well-known that young children have more difficulty in deciphering small and closely spaced symbols or objects. This phenomenon, called (foveal) crowding or masking, entails that discrimination deteriorates when the target is surrounded by distracters. Eye movement control and the development of selective attention have been suggested to play a prominent role in crowding. In the present study we will use a visual-search paradigm to study the effect of inter-symbol space (ISS) on the dynamic organisation of eye movements in 6- to 8-year-old children. Eye movements were registered at 60 Hz with a Tobii T120 eye tracker. A relation was found between ISS and the temporal structure of fixation timeseries, as quantified by recurrence analysis. A qualitative change in the rqa-measures occurred between ISSs of 8 and 16. No relation was present between ISS and fixation-difference timeseries. These results might partly be task specific, but are likely to reveal the changing (developing) relationship between attention, gaze, memory, and search processes.

Use noise to determine cardiac restitution with memory *Poster*

Shu Dai, James Keener

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Noise in cardiac pacing cycles, for instance, the heart rate variability, has been observed for decades. Contemporarily, various cardiac models have been constructed to investigate the electric activity of the cardiac cells. Yet there has not been a clear study for the cardiac models when there is noise in the pacing cycles. In this talk, we present a regression method to approximate the dynamics of cardiac cells when the pacing cycles are stochastic, assuming the underlying electric activity of the cardiac cells follows some mapping model with hidden memory.

Recurrence Spectroscopy: Classical Orbits and Quantum Spectra

John Delos

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Recurrences are directly visible in the absorption spectra of atoms in electric and magnetic fields. These recurrences are related to classical orbits of electrons going out from and later returning to the atom. The recurrences show up in real time, or as interference between waves emitted from and returning to the atom. As field strengths change, orderly orbits change to chaotic ones, and returning orbits bifurcate and proliferate. We will describe geometrical and topological methods that can give a minimal set of returning orbits.

Recurrence plot analysis of symbolic sequences. Application to behavioral data

Philippe Faure

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Symbolic sequence are widely used in animal behavior studies. Complex animal behaviors consist of a finite number of actions combined in a variety of spatial and temporal patterns. Considering a sequence of acts, a question would be whether information contained in the structure of this sequence and the presence of specific associations between acts reflects decisionmaking behavior and can be used to assess alterations of this process. We used recurrence plot (RPs) to analyze the recurrence of patterns ("words") through higher-order RPs, to dissect of the contribution of each specific pattern through analysis of partial RPs, to estimate the entropy and analyze nonstationary of the sequence.

On bi- and multivariate extensions of recurrence network analysis

Jan H. Feldhoff, Reik V. Donner, Jonathan F. Donges, Norbert Marwan, and Jürgen Kurths

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Recently, it has been suggested to reinterpret a recurrence plot as the connectivity matrix of a complex network associated with the time series under study. Statistical measures

characterizing the topology of such recurrence networks on both local and global scale have already demonstrated their great potential for detecting changes in the underlying dynamics as reflected in the geometry of the corresponding attractor in phase space.

Here, we introduce two possible extensions of the recurrence network approach for studying two or more potentially coupled dynamical systems. Specifically, the established concepts of cross- and joint recurrence plots, as well as the recently introduced graph-theoretic framework for describing the properties of interacting networks are utilized for deriving a corresponding complex network representation. We discuss the interpretation of both approaches in terms of the associated phase space properties and provide some examples highlighting their performance for studying interacting complex systems.

Studying and forecasting the atmospheric pollutants dynamics by using the non-linear prediction approach and recurrence plots method

A. V. Glushkov, O. Yu. Khetselius, G. P. Prepelitsa

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It is known that a chaos is alternative of randomness and occurs in very simple deterministic systems. Although chaos theory places fundamental limitations for long-rage prediction, it can be used for short-range prediction since ex facte random data can contain simple deterministic relationships with only a few degrees of freedom. Many studies in various fields of science have appeared, where chaos theory was applied to a great number of dynamical systems. The studies concerning non-linear behaviour in the time series of atmospheric constituent concentrations are sparse, and their outcomes are ambiguous. Our paper concerns results of the research into dynamics of variations atmospheric pollutants concentrations in the definite region by using the non-linear prediction approaches and the recurrence plots method. A chaotic behaviour in the nitrogen dioxide and sulphurous anhydride concentration time series at two sites in Odessa, Gdansk regions is investigated. To analyze measured time histories of the considered system responses with the use of the Recurrence Plots, the phase space of these systems was reconstructed by delay embedding. To reconstruct the corresponding attractor, the time delay and embedding dimension are needed. The former is determined by the methods of autocorrelation function and average mutual information, and the latter is calculated by means of correlation dimension method and algorithm of false nearest neighbours. Its shown that low-dimensional chaos exists in the time series under investigation. The spectrum of Lyapunov exponents is reconstructed as well as both Kaplan-Yorke dimension and Kolmogorov entropy that inversely proportional to the predictability limit are calculated.

Studying interaction dynamics of the nonlinear vibrational systems on the basis nonlinear prediction approach and recurrence plots method (application to semiconductor quantum autogenerators) *Poster*

A. V. Glushkov, V. M. Kuzakon, G. P. Prepelitsa, E. P. Solyanikova

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Paper is devoted to an employing a variety of techniques for characterizing dynamics of the coupled semiconductor quantum autogenerators and identifying the presence of chaotic elements. To analyze measured time histories of the vibrational systems responses with the use of the recurrence plots method the phase space of these systems was reconstructed by delay embedding. The mutual information approach, correlation integral analysis, false nearest neighbour algorithm, Lyapunov exponents analysis, and surrogate data method are used for comprehensive characterization. The correlation dimension method provided a low fractal-dimensional attractor thus suggesting a possibility of the existence of chaotic behaviour. The method of surrogate data, for detecting nonlinearity, provided significant differences in the correlation exponents between the original data series and the surrogate data sets. The main conclusion is that the system exhibits a nonlinear behaviour and low-D chaos.

Application of Recurrence Plots to long-term heart rate recordings for the analysis of circadian rhythmicity

Christian Heinze, Udo Trutschel, David Sommer, Martin Golz

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The ECG, which requires merely the application of electrodes to the skin, combined with a mobile recording device, provides a convenient measurement for emphcircadian rhyth-

micity. Due to a complex regulation by the autonomic nervous system and the suprachiasmatic nucleus, the emphheart rate (HR) time series is a highly variable and irregular signal. This work investigates if methods of emphnonlinear signal analysis can reveal circadian characteristics of long-term HR recordings.

We report on young male volunteers who participated in an unsupervised 50-hour data collection protocol during their normal daily routine. HR series were derived from recorded ECGs. Also, emphsubjectively rated sleepiness and emphmotoric activity (via wrist actometry) were recorded during measurements.

The *state space trajectories* of HR series were reconstructed by time delay embedding. emphRecurrence plots (RP) provide a 2-dimensional representation of all times when a trajectory revisits roughly the same area in state space. The interpretation of large- and small-scale patterns within a RP reveals different qualities – such as determinism, periodicity, chaos or intermittency – about the trajectory's time evolution. A sliding window (width 60 minutes, step size 1 minute) was moved over all HR series; for each window, RPs were constructed.

For all subjects, the occurrence of similar events during the recordings – like peaks and troughs of sleepiness, peaks of physical activity, transitions from sleep to wake or vice versa – resulted in a display of similar patterns in the corresponding RPs. Also, time series of quantitative RP-features revealed a strong sensitivity towards sleep episodes and the time of wake-up.

RQA – a means of predicting pressure relief movements in the prevention of pressure ulcers?

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Introduction: Pressure ulcers, painful and debilitating, are prevalent in the aging population. Pressure relief movements are used as the predominant preventive strategy. This study investigates if there are early indicators of pressure relief in the young and the elderly, with the aid of the Ballistocardiogram(BCG), a non-invasive method, which provides information on the acceleration profile of blood. Predominantly used for monitoring cardiac it is argued that the principle of the BCG may be used to sense also other small movements related to circulatory events in the systemic circulation, which are associated with and change prior to pressure relief. Two methods are compared in the detection of such events, windowed FFT and RQA. It was expected that a windowed RQA should be more powerful in timely detection of increasing discomfort, than a windowed FFT as the BCG signal is thought to be a nonlinear combination of interaction between body and support surface properties. Methods: Subjects (elderly $n = 12$, young $n = 12$) were asked to lay in supine position on a Permaflex Mattress for 60 min. and prompted to move, when they felt discomfort. Movements were recorded using a webcam. Electrocardiogram (ECG) was recorded with a 3-lead PowerLab/8SP (AD Instruments). BCG was recorded with an Emfit Bed Sensors (L-4060SL) positioned under the mattress. The time to first identified pressure relief movement of each subject was used as the time period subjected to a windowed FFT and a windowed RQA. RQA and windowed FFT were compared.

Results: On average the RQA was able to detect changes 30 (decrease in% recurrence, increase in ratio) and decrease in Entropy showed changes even 60 sec before a shift in the frequency band was evident.

Conclusions: Adaptive changes before pressure relief were present in both the young and older subjects with the RQA method detecting changes predictive of pressure relief 60 seconds earlier (entropy measure) that spectral linear analysis.

Recurrence plots for point processes and their application to earthquakes

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Recurrence plots broaden the spectrum of nonlinear time series analysis since recurrence plots can be applied to any time series if one defines their distance. In this presentation, we show that one can apply recurrence plots to point process data. First, we define a distance between point processes. Then, we check its validity by using point process data generated from toy models. Lastly, we apply the distance and recurrence plots to an event series of earthquakes. We will see that recurrence plots provide more useful information than they were originally intended to do.

Window Size Problem in Recurrence Quantification Analysis *Poster*

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Time-dependent RQA is a powerful tool for discovering transitions in the dynamics of a complex system. General way to create series of RQA measures is covering the RP with small overlapping windows of size w along the main diagonal and calculating RQA measures in each of these windows.

When starting to study data using time-dependent RQA, there are questions raised. What window size w should we take in each exact condition? Are results, calculated with selected w, correct and significant? Moreover, is it possible to choose appropriate window size using some formal criteria?

If the window is too small, it can show us fake information due to noise, low quality of data, random events because of weak statistical significance. On the opposite side, if the window is too large, it can hide something significant and makes time range of RQA series smaller. RQA measures are statistical measures, and so the window should be large enough to cover a sufficient number of structures of RP. But all of these general reasons do not say what the window size should be?

In this work, some dependencies between window size, studying data and calculated results are shown. Some criteria for choosing an appropriate window size are given.

Studying Asymmetry in Complex Systems Without Using CRPs

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CRPs allow us to study asymmetries in complex systems (e.g. Zolotova, Ponyavin, 2006, application to sunspots data). Analyzing of LOS of CRP can show us some information about phase asymmetry of two time series. But without additional processing, index LOS is not continuous.

In this work, a new method is introduced. We provide index of recurrence asymmetry (RR_{NA}). This index is calculated from results of quantification of two recurrence residuals plots (RRP). RRP is defined as

$$\begin{aligned} \mathbf{RRP} &= \left(1 - \Theta\left(\varepsilon_x - \left\|\vec{x}_i - \vec{x}_j\right\|\right)\right) \cdot \Theta\left(\varepsilon_y - \left\|\vec{y}_i - \vec{y}_j\right\|\right), \\ i,j &= 1 \ldots N. \end{aligned}$$

For example, each of two plots may be constructed from sunspots series of the Sun and each of its hemispheres correspondingly. After quantification of RRPs, a new index should be calculated by classic formula

$$RR_{NA} = \frac{RR_N - RR_S}{RR_N + RR_S}.$$

The difference between the new index and classic NA index and modern LOS index is shown. Four zones of sunspots asymmetry are described and estimation of their continuation is given. Of course, this method could be generalized to any complex system if we can measure three series of data one of all system, and one of each of two parts (for example, hemispheres of the Sun or the Earth).

Recurrence analysis and chaotic motion around Kerr black hole *Poster*

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We employ recurrence analysis to study the motion of charged test particles around a Kerr black hole immersed in the asymptotically uniform magnetic field. Such setup allows for stable off-equatorial orbits which we consider a basic model of the astrophysical coronae consisting of a diluted ionized gas circulating in the inner parts of the black hole accretion systems. We use recurrence plots as a tool to visualize recurrences of the trajectory in the phase space and compare them to the traditional method of Poincaré surfaces of section. We show that recurrence plots and their quantitative measures (RQA parameters) are powerful tools to detect dynamical regime of motion (regular vs. chaotic basically) and precisely locate the transitions between these regimes occurring in the given relativistic system.

Recurrence, visibility and correlation networks of calcium dynamics in pancreatic islets

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Network theory has been successfully used in exploring the structure of many complex systems in the last decade. In

biology, it seems that a particular organization of biological networks is common to biological systems at all scales.

Here, we shall present the construction of complex networks of pancreatic islets, a compact microorgans in which the release of insulin is under physiological conditions robustly controlled by an efficient cell-to-cell network communication.

The networks of insulin releasing beta-cells are formed based on measured time series data of calcium dynamics and on positional information obtained by image analysis of confocal functional imaging of intact islets in pancreatic tissue slices. Using the recurrence plots approach and the visibility algorithm we first compare and characterize the network representations of single time series. The islet networks constructed based on correlations of the calcium dynamics in the islet are compared with the network models of spatially embedded heterogeneous cells to seek the relationship between the structure and the function of the tissue.

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Using Recurrence Quantification Analysis for a detailed model-data comparison: the case of a water transport model

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In ecosystem research and elsewhere, calibration of multi-parameter process-oriented models using measured data is a tedious enterprise. Usually, the goodness-of-fit criteria are simple, utilizing overall performance measures like the sum of squared errors or the model efficiencies, augmented by visual inspection, focusing on rather basic properties of the observations only. No insight is gained into the dynamical properties of the model on different time scales in comparison to the measurements. In this situation, either of two things may happen: the model could be "good" with respect to the simple measures, but is not able to reproduce the observed dynamics; or the model could be "bad", e.g., wrongly scaled, but a more detailed look reveals that more advanced properties of the dynamics are captured by it nevertheless.

Recurrence Quantification Analysis (RQA) is a sensitive set of methods to determine dynamical properties in detail. RQA provides highly sophisticated model performance criteria. It is thus a stringent test bed for models, providing insights into the strengths and weaknesses of models in reproducing observations under different aspects. We demonstrate the potential of RQA for such a detailed model-data comparison through the example of a model which simulates water transport through the soil of a forest ecosystem. In this case, there is a hint from the determinism and entropy of Cross-RQA that the absence of a process related to the distribution of plant roots in the model limits its performance significantly. More general, we propose using RQA for model improvement or in the case of huge discrepancies as a basis for model rejection.

Analyses of electrocardiograph with the eyes of complex network theory: a snapshot

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In the latest years, extensive efforts have been witnessed to bridge time series analysis and complex network theory. In this talk, after a very brief review, I will mainly introduce some recent outcomes in the ECG time series analysis with complex network theory, and more steps further in near future.

Image processing using recurrence plots

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Diagnostics based in image analysis of digital images are very common nowadays. In fact many small lesions of a hu-

man tissue or scratches of a surface for example sometimes can only be barely detected by a trained eye. It is easy to find digital scanners able to produce 64,000 grey levels, a distinction much higher the the human eye. Here we propose a new method of analysis based on recurrence. We show that the image produced by the method can be easier handled and details not observed in the original untreated images can be unveiled.

Recent achievements in recurrence plot research

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In the last years some new directions in recurrence plot based research have been developed. I will give a brief overview about the recent developments, like network analysis of recurrence plots, analysing point processes, indirect couplings, or significance tests for recurrence plot structures and measures.

Application of recurrence plot to verify Taken's theorem in some dynamical systems

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The paper highlights the use of recurrence plot and recurrence quantification analysis (RQA) for verifying Taken's theorem in some dynamical systems. The aim is to show that a topological equivalence can be assured for given attractor of a dynamical system and its reconstructed attractor from one of its solution components. But topological equivalence needs at priory topology of the attractor and that of its reconstructed one and then a homeomorphism between the two sets. Naturally, verification of topological equivalence is not a straight forward process. In this context, we realize that if we can describe the nature of movement of the trajectory in the phase space of the original and reconstructed attractor, then in this geometrical sense it is possible to say whether topological equivalence is achieved or not. This is the place where RQA is found to be very much useful. In fact, we find such application of RQA in some dynamical systems.

Sequence signatures of allosteric proteins towards rational design

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Allostery is the phenomenon of changes in the structure and activity of proteins that appear as a consequence of ligand binding at sites other than the active site. Studying mechanistic basis of allostery leading to protein design with predetermined functional endpoints, is an important unmet need of synthetic biology. Here, we screened the amino acid sequence landscape in search of sequence-signatures of allostery using Recurrence Quantitative Analysis (RQA) method. A characteristic vector, comprised of 10 features extracted from RQA was defined for amino acid sequences. Using Principal Component Analysis, four factors were found to be important determinants of allosteric behavior. Our sequencebased predictor method shows 82.6% accuracy, 85.7% sensitivity and 77.9% specificity with the current dataset. Further, we show that Laminarity-Mean-hydrophobicity representing repeated hydrophobic patches is the most crucial indicator of allostery. To our best knowledge this is the first report that describes sequence determinants of allostery based on hydrophobicity. As an outcome of these findings, we plan to explore possibility of inducing allostery in proteins.

Application of Recurrence Quantification Analysis for the Study of Altered States of Consciousness *Poster*

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The study of altered states of consciousness has attracted the attention of many research workers and a large body of literature exists in this field. This work discusses novel application of recurrence quantification analysis (RQA) to the study of altered state of consciousness with particular emphasis on meditation and sleep. The study of meditation is important since it is a higher state of consciousness, an understanding of which can throw light on the basic understanding of the physiology of the systems involved; also it helps in gaining insight into physiological prerequisites responsible for improvement in health of both body and mind. We have applied RQA as a nonlinear time series analysis method to

heart rate variability (HRV) time series during meditation to discriminate between meditation state and pre-meditation state. The HRV time series are made uniformly sampled using cubic spline interpolation and then digitally filtered to remove noise. The preprocessed HRV has been segmented into 3 minute epochs before applying RQA. Various parameters are extracted from the recurrence plot such as recurrence rate, diagonal parameter (divergence), vertical or horizontal parameters (laminarity, max vertical length). We have considered two types of analysis conditions in this study. In the first case, RQA parameters are computed for various values of embedding dimensions and threshold parameter is set as mean of the distance matrix from which recurrence plot is derived. This corresponds to the relative threshold case where each epoch has different value of threshold. In the second case, we fixed embedding dimension value and threshold parameter is varied . This case corresponds to the absolute value of threshold parameter for fixed embedding dimension. In each of these cases, the values of RQA parameters are compared between meditation and pre-meditation states (considered as control) to discriminate between the states. Our results show that RQA parameters are very effective in discriminating the two states. Similar studies have been made on the application of RQA to data recorded during various stages of sleep and it has been found that RQA is very effective in distinguishing various stages of sleep.

Network approach for unveiling subtle transitions in dynamical systems *Poster*

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The present work shows that measures for the characterization of complex networks can be used as an efficient alternative to other existing tools of nonlinear analysis in order to unveal subtle transitions in the phase space of dynamical systems. An analogy between the recurrence matrix encoding the recurrences and closeness of phase space vectors of dynamical systems and the adjacency matrix of an undirected and unweighted complex network is exploited and some complex network measures are extracted. The potential of these recurrence network measures in unvealing different transitions in the dynamics of quasiperiodically forced systems is illustrated and attention is drawn to strange nonchaotic dynamics which is clearly depicted by those measures. Instances of (anti-) correlation of these complex network measures with the largest Lyapunov exponent are observed.

Recurrence Quantification Analysis of Electroencephalogram and Heart Rate Variability data with applications *Poster*

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This work is concerned with the application of Recurrence Plots to the study of complex biomedical systems. In the first application, multichannel EEG time series data recorded from the brain (viewed as a complex dynamical system) during electroconvulsive therapy (ECT) was used. An index called Correlation between Probabilities of Recurrence (CPR) (Kurths et al.), which quantifies phase synchronization, was used in identifying different physiological states of the brain. ECT is a procedure in which electric currents are passed through the brain, deliberately triggering a brief seizure, which causes changes in the brain that can alleviate symptoms of certain mental illnesses. CPR could distinguish between pre-seizure and seizure conditions through the 16 channel EEG time series data of 16 subjects who underwent ECT, since phase synchronization among various parts of the brain is more (as indicated by higher CPR values) during seizure than before seizure. Since the seizures were focal in nature, the channels corresponding to the focus showed maximum synchronization. Running multichannel synchronization of the whole data demonstrated the phenomenon clearly using successive contour plots of the obtained results. These studies clearly demonstrate the capability of the index CPR in detecting phase synchronization in human EEG. We also consider here the application of recurrence quantification analysis to Heart Rate Variability (HRV) data recorded under various experimental conditions. In this second application, we considered two measures namely the longest diagonal length (Lmax) and longest vertical line length (Vmax) of the recurrence plot. A new parameter MLV was defined based on Lmax and Vmax. The analysis was made for a large database recorded under supine and standing positions; results were also obtained for a large database of normal and abnormal HRV data. Tests were performed on the database to determine thresholds that can distinguish standing and supine data as well as normal and abnormal data. Using these thresholds, it was found that the proposed measure can distinguish normal from abnormal with 99% accuracy; also it can distinguish supine from standing with an accuracy of 95%. These results establish the potential of RQA for cardiac care applications, and the capability of recurrence plot based methods as a whole in studying complex biological systems.

Time series decomposition in terms of stochastic and deterministic components: an approach using recurrence plot and empirical mode decomposition

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System behavior studies have been conducted in several science domains such as Economy, Computer Science, Mathematics, Astronomy and Biology. In general, the outputs produced by real-world systems tend to present temporal dependencies and they are characterized by the interaction of multiple interconnected entities, which are referred to as subsystems or components. By estimating the functions (or rules) that describe the components of a system, it is possible, for instance, to take more accurate decisions, simulate and predict future situations, and also detect fail occurrences. A well-known way to estimate this rule is through the study of time series behavior according to stochastic and deterministic components. When such components are not correctly analyzed, the accuracy of applied models tends to reduce. Nevertheless, the decomposition of a time series into these components is not a simple task. A method currently used to decompose time series is the spectral analysis, which uses a collection of linearly independent vectors to represent data. In this sense, it was developed the Empirical Mode Decomposition (EMD) method, which allows to decompose non-stationary and nonlinear time series into a set of finite components, called Intrinsic Mode Functions (IMFs). By identifying the IMFs, important information embedded in the original series are revealed such as the determinism and stochasticity. However, the main challenge faced with EMD is to define which IMFs are used to describe every component. Aiming to overcome this drawback, we have developed an approach that employs Recurrence Plot (RP) to estimate stochastic and deterministic IMFs. According to this approach, EMD is applied on a time series and IMFs are obtained. Thus, the determinism ratio, which is provided by the Recurrence Quantification Analysis (RQA), of every IMF is computed. Then, IMF determinism ratios are compared against a predefined threshold. If the ratio is higher than the threshold, the IMF is considered deterministic. Otherwise, it is considered stochastic. The sum of stochastic IMFs represents the system stochastic behavior, whereas the sum of deterministic IMFs represents the deterministic one. Several experiments were performed to evaluate this approach, which proved that by applying it on noisy time series, the components are decomposed with accuracy.

Understanding coupling and synchronization in EEG of epileptic discharge using recurrence analysis *Poster*

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The emergence of epileptic seizure is not clearly understood and the phenomenon is characterized by a synchronous discharge of large population of neurons. In the study we have utilized the property of recurrence of dynamical systems in understanding the synchronicity of epileptic discharge we have the synchronization index from the recurrence distribution of the phase space. We have also compared the synchronicity with respect to cross coherence using the standard spectral measure. The results indicate that the enhanced synchronicity is observed during seizure and decreases to near baseline level following seizure. In contrast the cross coherence does not depict high synchronicity observed during seizure. Therefore the recurrence can be used in measuring the state of synchronicity in neuronal ensemble in various traits of brain function.

Reliability of Recurrence Quantification Analysis Measures of Hand Drawings

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Background: In rehabilitation, it is important to assess the hand fine skilled movements (e.g. writing or drawing) in addition to the common muscular strength tests. Fine movements have complex features that should be exploited using new nonlinear quantifiers. Inter-session reliability of such new measures should be assessed before employing them in clinical studies.

Method: Six healthy women drew two primitive shapes (circle and spiral) on a tablet digitizer. The data were recorded in two days, each with two trials. Time series were analyzed using RQA method. Day-to-day reliability was assessed using intera-class correlation coefficient.

Results: Among many RQA measures, DET and LAM were more reliable. Some measures were reliable for certain drawing shapes. TREND was a reliable measure (ICC=0.79) only in spiral drawings.

Conclusion: RQA provides reliable measures to exploit complex behaviors underlying hand drawings to assess fine movement of fingers which is of importance in clinical studies.

Nonstationary process of particles transfer in open split systems *Poster*

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Particle movement occurs in time and space. In the case of particle transfer in the free-molecular regime it's impossible to describe their movement by means of macroscopic equations and Boltzmann equation. The interaction of particles with the systems walls will be the defining factor of the particle motion in the systems. On the other hand, the flux of these particles can be analyzed as stationary or nonstationary. The studies of stationary and nonstationary processes of the particle transport mutually compliment each other and give a clear idea of particle flux structure in the systems. The problems of the stationary process of the particle transport were studied in [1-3] with the application by Monte Carlo method. In this work results of the computer experiment on determination of nonstationary particle flux from slit systems with the application of Monte Carlo method are introduced. Flying out from the condensed phase surface particles might fly out of the system and return in the condensed phase after several collisions with systems walls. Distributions and densities of distributions of particles which fly out the system are received for different models of communication with the surface of the condensed phase and the systems walls different times of particle adsorptions on the systems walls and the interval of the escape between the particles from the surfaces.

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On the reconstruction of a signal from its unthresholded recurrence plot subject to disturbances *Poster*

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We examine the information content of unthresholded recurrence plots (URPs) subject to disturbances. This is important for making valid inferences from URPs. In our recent work [1], we provided joint conditions on the embedding parameters (embedding dimension and the time-delay) which guarantee that a zero mean signal can be uniquely recovered from its URP up to a sign factor. For signals with a known frequency content, this permits the computation of values for the embedding parameters which lead to maximally informative URPs. When these uniqueness conditions are not satisfied, then it is possible for different morphologies in a signal to give rise to identical patterns in the URP or RP. The information content of binary (thresholded) RPs has been studied in [2] and [3]. We also refine the graph theoretic procedure of [1] which was developed to characterize the uniqueness conditions. Here, the reconstruction methods of [1] are employed to investigate the reconstructibility of a signal from a disturbed URP in particular for values of the time delay near a value which not satisfies the uniqueness conditions.

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Recurrence networks for discrete data

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There has been much recent interest in contructing networks from time series data, partly because doing so makes available a vast new suite of tools for nonlinear time series anal-

ysis. In this paper we introduce an alternative approach by which these techniques can be employed when the underlying time series is a discrete symbolic sequence with a small finite alphabet — obvious connections to Markov chains and nonlinear time series modelling will be discussed. A trivial extension to this method also means that it can be applied to continuous-valued scalar time series as well.

Blind Source Separation and Extraction Using Recurrence Quantification Analysis

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This presentation discusses different approaches for blind source separation (BSS) and extraction (BSE) in the context of deterministic and random signals. First of all, the BSS/BSE problem is introduced and its classical solution – which led to the development of independent component analysis (ICA) – is exposed. Afterwards, it is shown that recurrence quantification analysis (RQA) can also be employed to perform BSS and BSE of deterministic signals in noisy environments, which can be an interesting paradigm for solving the problem of denoising chaotic time series in the context of multisensor detection. Finally, it is shown that RQA can be equivalent to classical ICA by means of an information-theoretic approach even when only random sources are considered, which establishes an important link between different signal processing paradigms.

Joint recurrence analysis on EEG signals of schizophrenia patiens in multiple frequency bands

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In this talk, I would report results of joint recurrence plots of EEG signals measureed form schizophrenia patiens and control subjects. The recurrence plots of EEG waves at multiple frequency band (e.g., alpha band, theta band, and gamma band) are first examined, and the relationship among EEG waves at different frequency bands are further investigated with Joint recurrence plot. To compare the recurrence plots of schizophrenia patiens with those of control subjects, recurrence quantification analysis (RQA) is further applied, and statistic analysis is performed for the RQA measures obtained from patients and controls subjects so as to explore their difference in recurrence plots. Measures of RQA that may be sensitive to clinical scores are expected to be found.

Characterization of gas-solid fluidized bed hydrodynamics by recurrence plot analysis

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Recurrence plot (RP) and recurrence quantification analysis (RQA), as powerful statistical techniques, have been used for studying the dynamic behavior of gas-solid fluidized beds within pressure time-series signal. RQA variables (recurrence rate, determinism, laminarity and entropy) were calculated for the bubbling fluidized bed at different superficial gas velocities (ranging 0.1 to 1.2 m/s). The results showed that the RQA parameters can be used to study of the bed hydrodynamics significantly. Patterns within RP changed with different superficial gas velocities, and subsequently RQA parameters changed accordingly. These patterns showed that the fluidized bed system has three different hydrodynamic behaviors as superficial gas velocity increases; at low gas velocities, macro structures become more dominant, further increase in gas velocity empowers influence of finer structures on the hydrodynamic and finally the fluidization regime changes from bubbling to turbulent. It was shown that, the transition point from bubbling to turbulent velocity (UC) value, which is a function of the bubble characteristic, is implicitly related to the recurrence quantified values.

Recurrence patterns in risky decisions *Poster*

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People do not follow rational paradigms when making risky choices; most people behave more conservatively when the alternative choices are formulated in terms of loss. Two decision-making experiments examined participants choices as they changed between a risk of loss and a sure loss, recording the mouse movements of each response and eye movements during each choice trial. Recurrence quantification was used to investigate changes in dynamics around switching behavior and the dynamics of response trajectories in general.

Method for tuning the threshold for recurrence plots and its efficiency in recognizing different dynamical states through recurrence network analysis

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In the construction of recurrence plots ($R_{ij}(\varepsilon)$), tuning the threshold (ε) and choosing the best metric are still open problems which depend on the time series standard deviation, their Rényi entropy, edge density, clustering coefficient and other dynamical properties. A standardized method for tuning the threshold is critical, since it determines the topology of the associated recurrence network to the time series, which can be analyzed to find different dynamical behaviors independent of the particular evolution of the system over time. In this paper, we introduce a method for tuning the threshold for the recurrence plots associated to synthetic time series and its efficiency in recognizing all the dynamical states of such systems, according to the stabilization of the clusters in the associated recurrence networks. The metric for the distance between vectors in the phase space is considered Euclidean in all cases and is established using measurements of the standard deviation, considering the results shown by R. V. Donner et al. in [1], [2] and [3]. This method was tested for two kinds of synthetic time series. First, we tested time series built with transitions between three and seven different Ornstein-Uhlenbeck processes. Then we used time series simulating the different expression levels of genes p53 and Mdm2 for the case in which irradiation is present, based in the model designed by C. Proctor and A. Gray in [4] and [5]. Since this method accomplishes the goal of finding different dynamical states in the given time series, it projects as an efficient tool in the analysis of real systems.

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Connecting the dots in networks of grain kinematics

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We construct complex networks to analyze experimental data from digital image correlation measurements of grain kinematics of a sample of mixed masonry-concrete sand under plane strain compression. As in recurrence network analysis the issue of setting appropriate thresholds for connecting dots in phase space based on inter-point distances is present. We discuss two methods of determining network connectivity and argue that network statistics from both methods are useful in unravelling the rheology and failure of dense granular materials under compression, in particular, strain localization and the formation of shear bands.

Assessing Coupling Strength between Discrete Events using Cross Recurrence Quantifications

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Cross recurrence quantification analysis (KRQA) between paired signals requires that both signals be sampled simultaneously at the same digitization frequency. With a single fast digitizer, multiple signals can be sampled almost simultaneously. KRQA also requires is that the compared signals within the recurrence window be in the same magnitude range so as to minimize the distances between the two embedded vectors. Typically, this criterion is handled by rescaling the input data over the unit interval.

KRQA works very nicely for paired signal trajectories (continuous flows), but is not amenable to event analyses (discontinuous intervals). The reason for this is that summed

intervals on each channel drift in time with respect to each other. That is, fast events will generate numerous intervals in a short time whereas slow events will generate few intervals in a long time. In this case, KRQA will be restricted to the fewer number of intervals on the lower frequency channel.

To solve this dilemma, paired input time series (S1 and S2) consisting of discrete events (time intervals) occurring at different frequencies were resampled to generate two new time series (S1n and S2n) with the exact same number of points and synchronous in time. Signal S1n consisted of the percent overlap with S2n; signal S2n consisted of the percent overlap with S1n. Every time an event occurred in either channel, percents (range of 0% to 100%) were computed for both S1n and S2n.

Proof of concept was first confirmed using paired toy signals. Second, the new technique was applied to physiological data recorded from 20 medical students. Respiratory cycles, electrocardiograms, and foot-falls were recorded from subjects standing, walking and running on a treadmill. All signals were discretized into: 1) breath-to-breath respiratory intervals; 2) R-R waves in the electrocardiogram; or 3) step-to-step intervals in the walking/running states. Cross recurrence analysis was employed on the resampled vectors to quantify the degree of non-linear coupling between respiratory-heart, respiration-step, and step-heart correlations. For controls, standard linear cross-correlations were also run on the physiological signals. The forthcoming positive results are applicable to coupled discrete events of any kind. For example, KRQA may be useful in the field of neurophysiology when attempting to assess the degree of action potential couplings between two neurons.

Drawing links between time series and complex networks — Multiscale characterization on recurrence-based phase space networks constructed from time series

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Methods of nonlinear time series analysis which aim to construct the complex network representative of a scalar time series draw research interests nowadays. By drawing links between time series and complex networks, the networks from time series which inherit features of original dynamical system enable the usage of graph theory and complex network studying methods nonlinear time series analysis and thus can provide complementary information to the dynamical system. One of the advantages of the complex network method for studying time series is that complex network theory provides a tool to describe either important nodes, or structures that exist in the networks, at different topological scale. In this talk, by constructing the recurrence-based phase space networks, we study a range of network based measures at the local-, meso- and macro-scale and show how these measures relate to the dynamical properties of the underling system. We also extend previous work by provide a rigorous computational study of the effect of noise in the time series data on the results one can obtain: both for simulated and experimental data.

The Gear's Fault Recognition Based on Recurrence Quantification Analysis and Gaussian Mixture Model *Poster*

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In order to overcome the shortcoming of recurrence plot that can only supply the qualitative analysis to signals, the recurrence quantification analysis is used to analysis different fault modes gears vibration signal. The gear fault pattern recognition method that combined the gaussian mixture model with the feature vector that consists of determinism and laminarity is proposed. Based on the signals that acquired form gear fault experiment table, the proposed method is compared with RBF artificial neural network classification method by Re-substitution test, Jackknife test and independent data set test respectively. The classification results show that the higher discrimination can be achieved by the proposed method.

Recurrence quantification analysis based operative nonstationarity assessment for structural ambient vibration signals

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A RQA based method is proposed for structural ambient vibration response nonstationarity assessment in an operational sense. It is based on a comparison between global and local RQA measurement. One key problem, here, is to extract a sensitive feature standing for nonstationarity. A new RQA measurement is developed to solve this problem. Based

on this, we employ a statistical classification method to assess the degree of nonstationarity. The integrated approach is outlined, and practical issues related to its actual implementation are discussed. Then, the nonstationarity assessment results of ambient vibration response are provided for illustrating the approach and supporting its effectiveness. And last, discusses about the influence of nonstaitonarity to analyze and interpret the vibration data and indicates that the stationarity assumption for the vibration data measured on the structures is conditional valid.

Multiscale Recurrence Plot

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Recurrence Plot has become a very powerful tool to characterize the deterministic structure from time series, finding a wide array of applications in engineering, physics, medicine and biology, geography and so on. Traditionally, a recurrence plot contains typical small-scale structures, i.e., as single dots. Here we extend the traditional RP to one that can address the multiscale structure of the time series. To this end we coarse grain the time series at various temporal scales, and examine the RP statistics and see if there are any invariant properties with respect to different kinds of dynamics. This approach is a compliment to the traditional RP, and is expected to reveal the important multiscale organization of the data.

Are recurrence networks scale free?

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During the last years, intensive efforts have been spent on applying network-based concepts also for the analysis of dynamically relevant higher-order statistical properties of time series. Notably, many corresponding approaches are closely related with the concept of recurrence in phase space.

We report power law properties for recurrence networks reconstructed from time series sampled from deterministic dynamical systems. As an example, the scaling exponent of a generalized logistic map is analytically derived, showing irrelevance to dimension. In the case of continuous systems, it remains ambuiguous whether the degree distribution of the network follows a power law with an exponent depending on a suitable notion of local dimension or a power law of exponent 1. We illustrate the results by several prototypical dynamical systems and experimental CO_2 laser data.