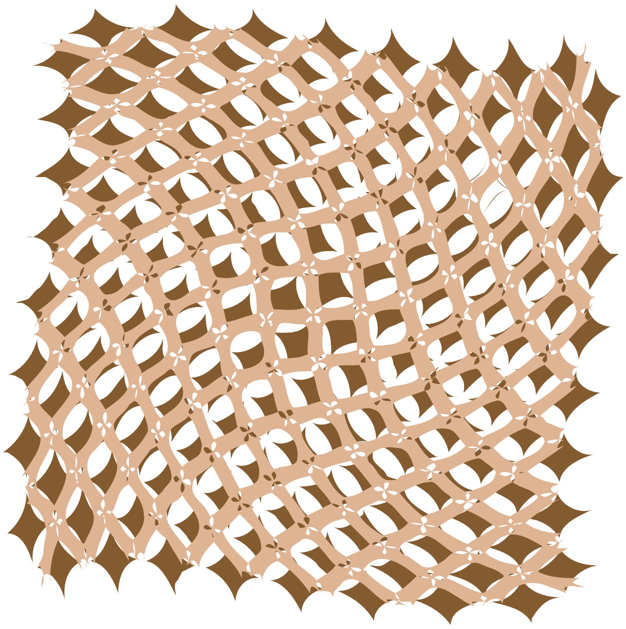
Programme

second international workshop on recurrence plots



Siena, 10-12 September 2007

www.recurrence-plot.tk/ws.php

University of Siena
Center for the Study of Complex Systems

Centro per lo Studio dei Sistemi Complessi

Scientific and Organisational Committee

Angelo Facchini[1]
Norbert Marwan[2]
Marco Thiel[3]
Antonio Vicino[1]
Holger Kantz[4]
Joseph Zbilut[5]
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Aims

In 2007 we have the anniversary of 20 years since the introduction of recurrence plots by Eckmann in 1987. In its honour, a second recurrence plot workshop is held at the Centro per lo Studio dei Sistemi Complessi in Siena (Italy), at September 10-12, 2007.

The objective of the workshop is the exchange of knowledge of scientists working in the disciplines of time series analysis and/or recurrences. Significant progress has been made in the areas of data analysis by means of recurrences. Recurrence Plots (RPs) have been shown to be a very robust tool for the analysis of time series, and can cope with large amounts of noise and even nonstationarity. RPs have found applications in fields such as physiology (EEG, ECG), astrophysics, geophysics, meteorology, genetics and finance. Theoretical results show how closely RPs are linked to dynamical invariants like entropies and dimensions. It can be shown that the dynamics of a system can be captured in a recurrence plot and that it is possible to perform a synchronization analysis by RPs. These practical and theoretical aspects will be discussed in the workshop. Moreover, potential applications of RP-based methods for spatio-temporal data, image analysis, statistical tests etc. will be explored.

Practical Workshop

In the workshop, 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.

Internet Access

There are two computers available for checking e-mails. It is only possible to read and write e-mails, but not to upload and download files. For this special need there is another PC in the secretary.

Social Event

It is planned to have a dinner at the "Santa Chiara" on Tuesday, 7.30 p. m. (cf. Location).

Location

Siena is the capital of the province of Siena and is located in Tuscany, Italy. The historic center of Siena has been declared by UNESCO a World Heritage Site.

Lectures

The workshop takes place in the auditorium of the *"Santa Chiara" doctoral school* of the University of Siena. The full address is:

Collegio Santa Chiara
Via Valdimontone, 1 - 53100 Siena

Tel.: 0577-235940/53
Fax: 0577-235939
E-mail: santachiara@unisi.it

It is located in the center, and it is easily reachable by feet from any point of the town.

Practical Workshop

The practical workshop takes place in the Computer-Room of the Engineering Faculty of the University of Siena. It is located near the *Collegio Santa Chiara* and can be reached by foot in about two minutes. Further information will be provided by the organising staff during the conference.

Special Issue

All contributors are invited to submit their work for a special issue of Physica D dedicated of the anniversary of recurrence plots: "20 Years of Recurrence Plots: Perspectives for a Multi-purpose Tool of Nonlinear Data Analysis". The standards for publication are as high as for a regular Physica D paper (and thus are in general substantially higher than the standards for acceptance in the workshop). All of the papers are expected to describe original research.

Authors are encouraged to write short articles (page limit of 8 pages, incl. figures). If someone feels that his/her material cannot be presented on 8 pages, the author might ask us before writing the article whether it is justified to have a longer article on a specific topic (review-like article).

For the submission of articles please use the online submission system located at
`http://www.ees.elsevier.com/physd`.

Note: To ensure that your manuscript is correctly identified for inclusion into the special issue, it is important that you select **"Special Issue: Recurrence Plots"** when you reach the *Article Type* step in the submission process.

The manuscripts should be submitted until September 30, 2007.

Further information (templates, submission procedure) is available on
`http://www.recurrence-plot.tk/ws.php`.


CSC
Auditorium Santa Chiara
PORTA CAMOLLIA
PORTA OVILE
PORTA LATERINA
PORTA ROMANA
PORTA TUFI
FONTEBRANDA
FORTEZZA MEDICEA
ENOTECA ITALIANA
S. DOMENICO
BASILICA DI S. FRANCESCO
ROCCA SALIMBENI
BASILICA DI PROVENZANO
UNIVERSITÀ
PALAZZO PICCOLOMINI
UNIVERSITÀ PER STRANIERI
IL CAMPO
PALAZZO PUBBLICO
DUOMO
SANTA MARIA DELLA SCALA
PALAZZO DELLE PAPESSE
PALAZZO CHIGI SARACINI
PINACOTECA NAZIONALE
S. AGOSTINO
MUSEO DI STORIA NATURALE
ORTO BOTANICO
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VIALE FEDERIGO TOZZI
LA LIZZA
VIA DEI BANCHI DI SOPRA
VIA DEI BANCHI DI SOTTO
VIA DI CITTÀ
VIA DEL CASATO
VIA DELLE CERCHIA

Programme

Monday, September 10th

8:30 Registration

Introduction

9:00 **A. Facchini**:
Welcome Note

9:15 **M. Thiel**:
Anniversary Talk 20 Years of Recurrence Plots

10:00 **N. Marwan, M. Carmen Romano, Marco Thiel**:
Introduction Lecture Recurrence Plots for the Analysis of Complex Systems

10:45 *Coffee break*

Methodological Aspects

11:30 **J. P. Zbilut**:
Keynote Lecture Laminar Recurrences, Maxline, Unstable Singularities and Biological Dynamics

12:25 **A. Schultz**:
Speech Analysis Using Recurrence Quantification Analysis

12:40 **C. Farinelli**:
Similarity Metrics and Complexity Measures in Biological Signals

13:00 *Lunch*

14:30 **Y. Hirata**:
Reconstructing Distance Matrices from Recurrence Plots

14:45 **K. Klimaszewska**:
Detection of the Pomeau-Manneville Intermittencies and Connected with them Bifurcations Using Recurrence Plots

15:00 **S. R. Lopes**:
Detecting Nonstationarities and Trends in Time Series

15:15 **E. J. Ngamga**:
Recurrence Analysis of Strange Nonchaotic Attractors

15:30 **C. Pennetta**:
Statistics of the Extreme Values in Presence of Intermediate-Term Correlations

15:45 **C. Mocenni**:
Defining New Measures of Image Complexity Using the Generalized Recurrence Quantification Analysis

16:00 *Coffee break*

16:30 **M. C. Romano**:
Keynote Lecture Estimation of the Direction of the Coupling by Conditional Probabilities of Recurrence

17:00 **A. Facchini**:
The Origin of Curved Patterns in Recurrence Plots

17:20 **K. Chandrasekaran**:
Reconstructing System Dynamics from Short Time Series

17:35 **Y. Zou**:
Recurrence Plots and Quasiperiodicity

Tuesday, September 11th

Applications in Biological Systems

9:00 **A. Giuliani**:
Keynote Lecture Ten Years of Recurrence Plots in Protein Science: What we Learned

9:55 **S. Angadi**:
Nonlinear Signal Analysis to Understand the Dynamics in the Protein Sequences

10:15 *Coffee break & Poster Session*

Workshop

11:30 **Ch. L. Webber Jr.**:
Usage of RQA Software

12:00 **N. Marwan**:
Introduction in the CRP Toolbox

12:30 **A. Schultz**:
Analyzing Locally Recurrent Structure in non-Thresholded Recurrence Plots

13:00 *Lunch*

14:30 **Practical Tutorials**

19:30 *Social Event*

Wednesday, September 12th

Applications in Earth Sciences

9:00 **S. Li**:
Identifying Spatial Pattern of NDVI Time-Varying Complexity Using Recurrence Quantification Analysis – A Case Study in the Region Around Beijing, China

9:15 **E. N. Macau**:
Analyzing the Amazonia Forest Process of Interacting with the Biosphere

9:30 **R. Proulx**:
Multivariate Recurrence Plots for Visualizing and Quantifying the Dynamics of Spatially Extended Natural Systems

9:45 **M. B. Siek**:
Cross Recurrence Plots in the Analysis of Extreme Ocean Storm Surges

10:00 **J.-M. Zaldivar Comenges**:
Recurrence Quantification Analysis as a Method for the Detection of Environmental Thresholds

10:15 **N. Zhukova**:
Recurrence Quantitative Analysis of Stick Slip Acoustic Emission Dynamics under Small Periodic Electromagnetic Forcing

10:30 *Coffee break*

Applications in Economics

11:00 **P. Crowley**:
Analysis and Visualization of Synchronicity in Euro Area Business and Growth Cycles

11:15 **M. Faggini**:
Chaos Detection in Economic Time Series – Metric versus Topological Tools

11:30 **F. Strozzi**:
Recurrence Quantification Analysis and State Space Divergence Reconstruction for Financial Time Series Analysis

11:45 **R. Donner**:
Measuring the Performance of Manufacturing Networks by Recurrence Quantification Analysis

12:00 *Lunch*

Applications in Engineering

13:30 **T. Grabowski**:
Applications of Recurrence Plots in Road Traffic Analysis

13:45 **S. Hermann**:
Using Recurrence Plots to Quantify Levels of Automobile Drivers Discomfort over Time

14:00 **N. Jin**:
Multi-scale Recurrence Plot Analysis of Oil-Water Two Phase Flow Structure Based on Measuring Conductance Fluctuation Signals

14:15 **T. Karakasidis**:
Application of Recurrence Quantification Analyis of Temperature Time Series of Horizontal Round Heated Jet

14:30 **S. Horai**:
Cross Recurrence Plot Analysis on Interactive Calling Behavior of Two Japanese Tree Frogs

Poster

Applications in Biological Systems

Poster 1 **C. Xiao Zhou**:
Complexity Analysis of RNA Sequences with Recurrence Plot

Poster 2 **M. Śmietanowski**:
Cardiorespiratory Interaction during Simulated Sleep Apnea Explored by Joint Recurrence Plot Analysis

Poster 3 **M. Godoy**:
Standardization of Recurrence Plot Values in Healthy Young Adults

Poster 4 **M. Godoy**:
Recurrence Rate and Determinism by Recurrence Plot Analysis in Premature and Full-term Infants

Poster 5 **M. Stephan**:
Anaesthetics Differentially Affect Fluctuations in Haemodynamic Rhythms

Poster 6 **F. Saccomandi**:
Recurrence Plots (RP) and Recurrence Quantitative Analysis (RQA) Disclose the Dynamical Structure of Human Sleep from its Microstructure

Applications in Earth Sciences

Poster 7 **N. Marwan**, S. Breitenbach:
Detection of Climate Transitions in Asia Derived from Speleothems

Poster 8 **M. Stephan**:
Recurrence Quantification Analysis of Meteorological Time Series

Applications in Engineering

Poster 9 **G. Litak**:
Dynamics of the Cutting Process by Recurrence Plots

Poster 10 **R. Longwic**:
Recurrence Plots for Diesel Engine Variability Tests

Poster 11 **T. Živković**:
Low-dimensional Dynamics in Magnetized Plasma Turbulence

Abstracts

Nonlinear Signal Analysis to Understand the Dynamics in the Protein Sequences.

Savita Angadi

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Recurrence plots are a useful tool to identify structure in a data set in a time resolved way qualitatively. Recurrence plots and its quantification has become an important research tool in the analysis of nonlinear dynamical systems. In the present work, we utilize the recurrence property to study the protein sequences. The sequences that we analyze belong to two distinct classes, viz., soluble proteins and proteins that form inclusion bodies when over expressed in Escherichia coli. We study the underlying dynamics and extract the information which codes the essential class of a protein using recurrence quantification. We use Kyte-Doolittle hydrophobicity scale in the analysis. The results give meaningful insights to the level of understanding the protein sequence dynamics.

Reconstructing System Dynamics from Short Time Series

Komalapriya Chandrasekaran

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Long time series is the prime requirement of the time series analysis techniques to reveal the dynamics of a system. Here we try to address the question that given many segments of short time series, is it still possible to understand complete dynamics of the system under investigation ? The key idea is to generate a longer time series from the shorter segments, using the idea of recurrences. The so generated long time series are quite capable of exhibiting the dynamics similar to the long time series obtained from the same system.

Analysis and Visualization of Synchronicity in Euro Area Business and Growth Cycles

Patrick Crowley

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Synchronization of business and growth cycles is an important issue in the efficient formulation of euro area monetary policy by the European Central Bank. Although several studies in the economics literature address the issue of synchronicity of growth within the euro area, this is the first study to address this issue using cross recurrence quantification analysis. The general findings are that growth rates in the core of the euro area appears to be well synchronized, but the more geographically dispersed parts of the euro area appear to possess much lower levels of growth synchronicity with the rest of the euro area.

Measuring the Performance of Manufacturing Networks by Recurrence Quantification Analysis

Reik Donner

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In present-days global economies with their gradually increasing complexity and variety of products and services, the appropriate planning and control of manufacturing systems, their logistics, and the production processes themselves is an extremely challenging task. Consequently, a fundamental understanding of the mechanisms leading to unstable or irregular dynamics of the material flows in these systems is necessary.

In this contribution, we use recurrence quantification analysis (RQA) as a quantitative framework for an investigation of the dynamics of small-scale manufacturing networks. In particular, measures from RQA are estimated to characterize the regularity of the production process under a given external market demand. We compare the results for discrete-event simulations and continuous-flow models of different topologies which represent simple networks of collaborating manufacturers. The performance of the considered systems in the presence of different production as well as order strategies is evaluated and critically discussed.

Our qualitative and quantitative results allow to develop an anticipative knowledge about the performance of manufacturing systems under different conditions, which is of major importance for the planning and control of both, production and logistics. The potential implications for one specific real-world manufacturing network are discussed in some detail.

The Origin of Curved Pattern in Recurrence Plots

Angelo Facchini[1], Holger Kantz[2]

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[2]*Max Planck Institute for the Physics of Complex Systems, Dresden, Germany*
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We give a theoretical explanation of the formation of the curved macropatterns in the recurrence plots of sinusoidal signals, with nonstationarity in the phase or in the frequency. We show that the large time scales observed and the curved structures are the artificial product of the discretization of the signal. Recurrence Plots are highly sensitive to the phase error introduced by the sampling, and we show that this characteristic can be used to detect very small ($\sim$0.5%) phase or frequency shifts of the carrier frequency.

Chaos Detection in Economic Time Series – Metric versus Topological Tools

Marisa Faggini

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In their paper Frank F., Gencay R., and Stengos T., (1988) analyze the quarterly macroeconomic data from 1960 to 1988 for West Germany, Italy, Japan and England. The goal was to check for the presence of deterministic chaos. To ensure that the data analysed was stationary they used a first difference then tried a linear fit. Using a reasonable AR specification for each time series their conclusion was that time series showed different structures. In particular the non linear structure was present in the time series of Japan. Nevertheless the application of metric tools for detecting chaos (correlation dimension and Lyapunov exponent) didn't show presence of chaos in any time series. Starting from this conclusion we applied a topological tool Visual Recurrence Analysis to these time series to compare the results. The purpose is to verify if the analysis performed by a topological tool could give results different from ones obtained using a metric tool.

Similarity Metrics and Complexity Measures in Biological Signals

Chiara Farinelli

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I'll show the use of suitable similarity measures or information distances for extracting useful information out of different biological signals, such as DNA or protein sequences and also ECG signals.

Some of these distances are part of the so-called information distances based on the conditional Kolmogorov complexity of symbolic sequences. I will discuss their approximations by means of several heuristic and computable algorithms; such as compression algorithms or through the computation of the so called "Lempel-Ziv (LZ) complexity" based on a suitable parsing (i.e. a partition into substrings) of any given string.

Concerning again sequences similarity and related classification, clustering and searching problem, other several kind of distances will be analyzed: in particular the n-grams distances that exploits the frequency of words in sequences, or few new entropy methods suitable, in our opinion, to approximate the Kullback-Leibler "distance" (relative entropy), such as the Burrows-Wheeler transform or the so called non-sequential recursive pair substitution recently introduced by P. Grassberger.

Ten Years of Recurrence Plots in Protein Science: What we Learned *(Keynote Lecture)*

Alessandro Giuliani

Environment and Health Department, Istituto Superiore di Sanitá, Roma, Italy
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In these last ten years our group had the occasion to apply Recurrence Quantification Analysis technique to many facets of protein science going from molecular dynamics to the study of sequence and 3D structure of different protein systems.The peculiar character of intrinsic geometry of RQA allowed to obtain a fresh look to protein science that shed a new light to protein folding and aggregation mechanisms. On a methodological point of view, the enlargement of time series perspective to spatial (and wildly non stationary) series like biopolymers are and to three dimensional objects structures allowed to explore new and partially unexpected features of recurrence based techniques.

Standardization of Recurrence Plot Values in Healthy Young Adults *(Poster)*

Moacir Godoy

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Introduction: Heart rate variability (HRV) parameters have been used to characterize the normal functional condition of the autonomic nervous system from childhood to senescence. The recurrence quantification analysis (RQA) is an alternative tool to quantify the complexity even in rather short time series being independent of limiting constraints such as data set size, data stationarity, and assumptions regarding statistical distributions of data. So, the aim of the present study was to standardize RQA values in a group of healthy young adults for future comparative studies in groups with diseases.

Casuistic and Methods: Were included 20 normal healthy young adults. The mean age of the group and respective standard deviation was 20.1± 1.2 years and 11(55.0%) were male. In all of them were studied time series of 1, 000 beat-to-beat RR intervals (captured with the aid of Polar Advantage S810i equipment). The variables studied were Recurrence Rate (RR), Determinisn (DET), Averaged diagonal line length (Lmean), Entropy (ENT) and Laminarity (LAM). The software was available at http://www.agnld.uni-potsdam.de/˜marwan/rp/rp_www.php. The embedding and recurrence plot parameters were: $m = 1$, $\tau = 1$ and $\varepsilon = 0.1$.

Results: Mean, Standard Deviation, Maximum value, median, minimum value, range and variance coefficient are shown in the following table.

	RR	DET	LMEAN	ENT	LAM
Mean	0.0076	0.02139	2.0164	0.0661	0.0308
SD	0.0058	0.02419	0.0247	0.0942	0.0271
Maximum	0.0311	0.11879	2.0714	0.2573	0.1357
Median	0.0069	0.01547	2.0000	0.0000	0.0240
Minimum	0.0036	0.00452	2.0000	0.0000	0.0060
Range	0.0275	0.11427	0.0714	0.2573	0.1297
Varcoef	0.7664	1.13094	0.0123	1.4238	0.8791

Conclusion: Values of Recurrence Plot Analysis in healthy young adults and with the parameters utilized are very low showing that this group has a behavior of a complex nonlinear system. This is in agreement with a homeostatic (normal) pattern. These results can be useful for future comparisons with groups presenting pathological conditions.

Recurrence Rate and Determinism by Recurrence Plot Analysis in Premature and Full-term Infants *(Poster)*

Moacir Godoy

Sao Jose do Rio Preto Medical School – FAMERP, Brazil
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Introduction: Heart rate variability (HRV) parameters have been used to predict risk in patients with structural heart diseases or other pathological states and also to characterize the normal functional condition of the autonomic nervous system from childhood to senescence. It is possible to study the HRV with the aid of the traditional linear parameters but they only provide limited information about the underlying complex system. The recurrence quantification analysis (RQA) is an alternative tool to quantify the complexity even in rather short time series being independent of limiting constraints such as data set size, data stationarity, and assumptions regarding statistical distributions of data. The RQA methodology is fully applicable to any rhythmical system, whether it be mechanical, electrical, neural, hormonal, chemical or even spatial. So, the aim of the present study was to investigate how RQA behaved comparatively in temporal series of heart beats in premature and full-term infants.

Casuistic and Methods: Were included 99 subjects, being 29 prematures (Group A) and 70 full-term infants (Group B). Group A had a median age of 17 days (0 to 96) and group B a median age of 1 day (0 to 3). In all of them were studied time series of 1, 000 beat-to-beat RR intervals (captured with the aid of Polar Advantage S810i equipment). The variables studied were Recurrence Rate RR and Determinisn DET. The software was available at http://www.agnld.uni-potsdam.de/˜marwan/rp/rp_www.php. The embedding and recurrence plot parameters were: $m = 1$, $\tau = 1$ and $\varepsilon = 0.1$.

Results: Mean±Standard Deviation and [Median] for RR and DET in Group A were respectively: 0.017120±0.007686 [0.015036] and 0.151784±0.07917 [0.125389]. Mean±Standard Deviation and [Median] for RR and DET in Group B were respectively: 0.011796±0.004529 [0.010643] and 0.092894±0.05598 [0.082589]. For the Recurrence Rate the best cut-off value was ≥0.012249 and for Determinism the best cut-off value was ≥0.095056. So, for the Recurrence Rate variable the ODDS Ratio was 8.123077 (CI95% = 2.561591 to 29.981091; P<0.0001) and for the Determinism variable ODDS Ratio was 7.644444 (CI95%=2.416814 to 28.193057; P¡0.0001).

Conclusion: Recurrence Rate and Determinism are good markers to differentiate premature from full-term infants. Recurrence Rate and Determinism were higher in prematures confirming that they have a less developed, and so, more linear and less complex autonomic nervous system than full-term infants.

Applications of Recurrence Plots in Road Traffic Analysis

Tomasz Grabowski

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This paper deals with the problem of analysis of road traffic parameters based on measurements. Increasing number of vehicles on the roads in Poland and other countries has motivated development of electronic sensing techniques for measuring and analyzing traffic conditions. Huge amount of data are gathered using these techniques. Analysis of these data is not a trivial task. Several different methods have been proposed in recent years. Some of them (e.g. statistic methods) rely on analysis of probability and the underlying mathematical formula (pattern) is in most cases not known and it may be difficult to understand. Another approach proposed is so-called direct method which relies on a system for counting vehicles and measuring their specific features, such as: velocity, length, total weight, number of axles. Implementation of such a system includes inductive loops and piezoelectric sensors placed under the road surface. Based on the measurement it is possible to determine the class of vehicle. Since sometimes results of measurements are not easy to understand visualization methods should be introduced. This article presents discussion concerning description of the road traffic by method recurrence plots. Based on time series measured using standard equipment installed on the roads near Krakow we constructed various representations of the measured signals and constructed recurrence plots revealing special pattern and properties. Obtained plots are also compared with plots obtained for the internet traffic and frequency of phone calls in big company.

Using Recurrence Plots to Quantify Levels of Automobile Drivers Discomfort over Time

Sonja Hermann

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Recurrence plots were used in the current study to identify patterns of increasing sitting postural discomfort of an automobile driver over a few hours of driving in a real traffic situation. Consecutively recurrence plots of the Center of Pressure (COP) , the pressure under the ischial tuberosities (IP) and pressure under the upper thighs (TH) were constructed for the subjects (n=10). Recurrence plots of IP and TH data served as a discomfort reference for validating if the COP data recurrence plot would be able to serve as a single measure to validly describe levels of discomfort. By visual inspection and using recurrence quantification measures it could be demonstrated that the structure of the COP recurrence plots reliably portrayed the change in discomfort perception over the time of a drive. It was concluded that the COP measure holds the potential to serve as a possible measure as to reveal transitions of discomfort over time. Recurrence plots showed a clear change in the underlying dynamics of the data in relation to the persons perceived discomfort level and could be beneficial as a method for identifying changes in a persons discomfort levels. They also could be of great value when recording other subjective measures, serving as a potential alternative for questionnaires in circumstances where questionnaires cannot reliable portray the differences in levels of felt perception.

Reconstructing Distance Matrices from Recurrence Plots

Yoshito Hirata

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Recently it has been shown that from recurrence plots, we can estimate various dynamical invariants such as correlation dimension and correlation entropy. Therefore, it seems that recurrence plots contain much information of original time series. A question is how much they do. In this presentation, we demonstrate that recurrence plots possess almost all topological information of original time series by two ways: the first is by recovering shapes of original time series from recurrence plots; the second is by estimating generating partitions from recurrence plots. The key ingredient is reconstruction of distance matrices from recurrence plots. As a by-product, we can also estimate maximal Lyapunov exponents using recurrence plots.

This work is co-authored by Shunsuke Horai and Kazuyuki Aihara, both of whom belong to Aihara Complexity Modelling Project, ERATO, JST and Institute of Industrial Science, The University of Tokyo.

Cross Recurrence Plot Analysis on Interactive Calling Behavior of Two Japanese Tree Frogs

Shunsuke Horai

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We experimentally recorded spontaneous calls of two interacting male Japanese tree frogs (*Hyla japonica*). Two different calling data mainly corresponding to respective frogs were extracted from the recorded calling sound by using the free and cross-platform sound editor Audacity. We qualitatively analyzed the nonlinear and nonstationary dynamics of the interactive calling behavior of two frogs by the cross recurrence plot (CRP) and the analysis analogous to CRP, namely the order recurrence plot and the cross iso-directional recurrence plot. The results revealed complex interaction between a pair of two male frogs.

Multi-scale Recurrence Plot Analysis of Oil-Water Two Phase Flow Structure Based on Measuring Conductance Fluctuation Signals

Ningde Jin

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Oil-water two phase flow phenomena is very common in petroleum exploration and development, the pressure drop calculation and interpretation of production logs in oil wells require knowledge of flow patterns behavior. At present, it is fairly difficult to predict the flow patterns that will occur for a given set of flow rates and fluid properties. Although important progress has been made on the study of oil/water flow patterns, some problems are still unsolved. Various criteria of flow patterns identification lead to different prediction results. Some observed flow patterns are extremely dependent on the researchers subjective understanding. Consequently, the tendency is to give an objective indicator of flow patterns that is beyond the arbitrary decision. In this paper, the conductance fluctuating signals of oil-water two phase flow are firstly processed by wavelet analysis method, and then the recurrence plot analysis method is applied for analyzing the multi-scale signals. The results indicate that recurrence plots of different scale signals reflect the flow structure characteristic of oil-water two phase flow from low frequency to high frequency. We can effectively use the multi-scale recurrence plot analysis method to identify the typical oil-in-water and transitional flow patterns, and finally the oil-water two phase flow pattern map has been established. We conclude that the recurrence plot analysis method is a powerful tool to characterize the flow structure of oil-water two phase flow.

The project is co-funded by the European Union, European Social Fund & National Resources, EPEAEK II.

Application of Recurrence Quantification Analyis of Temperature Time Series of Horizontal Round Heated Jet

Theodoros Karakasidis

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In the present paper we present results concerning time-series analysis of temperature fluctuations in a horizontal round heated jet. Instantaneous temperature time series were recorded at several points across a horizontal line of the jet as a function of their distance from the center line. The times series are analysed using recurrence quantification analysis. The variation of the characteristic RQA quantities is associated with and interpreted via the transitions of the physical state of the flow from the center line to the boundary of the jet.

Detection of the Pomeau-Manneville Intermittencies and Connected with them Bifurcations Using Recurrence Plots

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One of the common routes to chaos is intermittency. The identification of the intermittency type is usually made on the basis of the probability distribution of the laminar phases and the average length of the laminar phases. Both properties have a statistical character, thus to obtain them a long time series has to be examined. Here, we present a Recurrence Plots method, with which a short time series can be analyzed and the identification of the type of intermittency be made. The three types of intermittency introduced by Pomeau and Manneville were examined. The identification of the type of intermittency is equivalent to the identification of the bifurcation associated with it. Our result seems particularly interesting as our method allows the analysis of short time series.

Identifying Spatial Pattern of NDVI Time-Varying Complexity Using Recurrence Quantification Analysis – A Case Study in the Region Around Beijing, China

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Description and characterization of complex phenomena observed in nature, which show generally a nonstationary and complex behavior, is of vital interest for ecologists. Probing the time-varying complexity of NDVI (Normalized Difference Vegetation Index) series plays an important role in predicting the variation of ecosystem. We have computed the complexity of monthly NDVI series from 1982 to 2000 in the region around Beijing, China by using RQA method, and then the spatial patterns of RQA indices such as RR, DET, ENTR, LAM, and TT etc. are exhibited with the support of GIS (Geographic Information System), and finally the causative factors resulting in spatial patterns of NDVI complexity are analyzed by synchronization index of bivariate analysis and logistic model. The results indicate that RQA-based complexity of NDVI and the spatial patterns have significant region differentiation in study area, and they are characterized by high complexity in the south of alluvial plain, medium complexity in the north of plateau and low complexity in the middle part of mountain. Anthropenic disturbances such as land use conversion contribute significantly to the formation of spatial patterns of NDVI complexity, while climatic factors have no obvious effect on it. RQA provides an alternative approach to measuring the complexity of ecosystem and its spatial pattern.

Dynamics of the Cutting Process by Recurrence Plots *(Poster)*

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The cutting process is a highly nonlinear phenomenon where dry friction is combined with possible contact loss and time delay effects. Unwanted and harmful vibrations may appear during cutting which may have a regular or chaotic nature depending on the system parameters. We have examined the cutting process by using a two degrees of freedom non-smooth model with a dry friction component [1-3]. Using nonlinear time series embedding approach and recurrence plots analysis we identify the cutting forces that may lead to a chaotic motion.

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Recurrence Plots for Diesel Engine Variability Tests *(Poster)*

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We examine fluctuations of a maximal pressure and the associated crankshaft angle in the diesel engine. By using recurrence plots and quantification analysis we identified instabilities in combustion process for various system parameters. The strong periodicities appear in low frequency bands and may persist over many cycles, whereas the intermittency is present at higher frequencies. The results may be useful to develop effective control strategies for an efficient engine performance.

In collaboration with G. Litak (Lublin) and A. K. Sen (Indiana).

Detecting Nonstationarities and Trends in Time Series

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The concept of recurrence was originally proposed by Poincaré at the end of the 19th century [1]. Nevertheless, it was just around 1987 that Eckmann et al. [2] introduced the method of recurrence plots nowadays used to reveal dynamical properties of systems such that non-stationarity of space or time series as well as to indicate the degree of aperiodicity [3, 4, 5]. In this study we use a prototypical model, specifically, a coupled map lattice (CML) $\vec{x}_{n+1} = \vec{f}(\vec{x}_n, \varepsilon)$, where ε is a coupling strength parameter limited in the interval $[0, 1]$ to generate chaotic time series. In such interval of ε the system presents different classes of behavior, from non synchronized to completely synchronized chaotic states. We demonstrate how we can use quantification analysis based in recurrence plots to bring up informations about the dynamics of a system [6]. The analysis is performed in stationary as well as in non-stationary time series (here a non-stationary time series is generated using a time series for a non fixed value of ε). For these cases we claim that it is possible to detect nonstationarities of the system caused by the transition "chaos — hyper-chaos". It is possible due to the presence of an invariant manifold embedded in the phase space. For these class of problem it is shown that it is also possible to use quantification analysis of the recurrence plots to detect and quantify the characteristics of the transition "chaos — hyper-chaos" (intermittency for example). The method is robust to noise and we suggest that this analysis can be important to detect non-stationarity behavior of experimental time series.

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Analyzing the Amazonia Forest Process of Interacting with the Biosphere

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In this work, we use the recurrence plot as the main tool for understanding the complex processes of interaction between the Amazonia rain forest and the terrestrial biosphere. The main issue is to understand the relations that mediate the exchange of heat and air flow circulation in the vegetation-air interface and how their dynamics changes from day to night. A proper understand of these dynamical processes allows the implementation of strategies for preservation of the Amazonia forest. Our results are based on *in situ* measurements that were carried out during the wet season, from January to March 1999 in a densely forested area. The measurements were made using a micrometeorological tower, simultaneously at three different heights: above the canopy (66 m), at the canopy (35 m), and within the canopy (21 m).

Recurrence Plots for the Analysis of Complex Systems *(Introduction Lecture)*

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Recurrence is a fundamental property of dynamical systems, which can be exploited to characterise the system's behaviour in phase space. A powerful tool for their visualisation and analysis called *recurrence plot* was introduced in the late 1980's. In this talk we give an overview covering recurrence based methods and their applications with an emphasis on recent developments. After a brief outline of the basic idea of the recurrence plot with its variations, we present different quantitative approaches. This includes the recurrence quantification analysis, which is highly effective to detect, e. g., transitions in the dynamics of systems from time series. A main point is how to link recurrences to dynamical invariants and unstable periodic orbits. As the respective phase spaces of two systems change due to coupling, recurrence plots allow studying and quantifying their interaction. This fact also provides us with a sensitive tool for the study of synchronisation of complex systems.

Detection of Climate Transitions in Asia Derived from Speleothems *(Poster)*

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Speleothems offer archives of climatic variability in the past. We analyse isotope records of stalagmites from three caves at different locations in Asia: Oman, Northern India and China. These records are proxies for the rainfall variability at these locations and cover a time range between about 3 and 4 kyr. At these locations, the influences of the summer and winter monsoon are rather different.

Recurrence is a fundamental property of dynamical systems. A statistical analysis of recurrence plots can uncover hidden transitions in data series, which are not obvious using linear statistical methods.

The analyses of the recurrence structure of the isotope records of the stalagmites reveals transitions at the same times, although the data series itself do not correlate. This result suggests that at these times the entire monsoon system underwent changes which are visible in the isotope records despite the different reaction of the local rainfall on the summer and winter monsoon.

Defining New Measures of Image Complexity Using the Generalized Recurrence Quantification Analysis

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By means of the Generalized Recurrence Plot (GRP) and the Generalized Recurrence Quantification Analysis (GRQA) [1], we analyze images showing complex patterns such as turbulent flows, fractals, and noise. Furthermore, we focus on snapshots of spatio-temporal processes such as the formation of Turing structures and travelling waves in the Belousov-Zhabotinsky reaction, and satellite images of spatial chlorophyll distribution in seas and oceans (http://oceancolor.gsfc.nasa.gov).

We focus on two RQA measures defined on the GRP, Entropy (ENT) and Determinism (DET), and we introduce the DET-ENT diagram, providing a new method for the classification of images based on their complexity content.

The comparison of the DET-ENT diagram with the classical image analysis entropy [2] defined on the pixel's values is performed: the method proposed in this paper performs better in the case of images showing complex spatial patterns.

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Recurrence Analysis of Strange Nonchaotic Attractors

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We present new methods to detect the transitions from quasiperiodic to chaotic motion via strange nonchaotic attractors (SNAs). These procedures are based on the time needed by the system to recur to a previously visited state and a quantification of the synchronization of trajectories on SNAs. The applicability of these techniques is demonstrated by detecting the transition to SNAs or the transition from SNAs to chaos in representative quasiperiodically forced discrete maps. The fractalization transition to SNAs, for which most existing diagnostics are inadequate, is clearly detected by recurrence analysis. These methods are robust to additive noise, and thus can be used in analyzing experimental time series.

Statistics of the Extreme Values in Presence of Intermediate-Term Correlations

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The return time statistics (RTS) of the extreme values in time series with long-term correlations has been recently studied by Bunde et al. [1] and Altmann and Kantz [2]. In this talk, the RTS of time series characterized by finite-term correlations with non-exponential decay will be considered. Precisely, the results will be discussed of numerical analyses of the return intervals of extreme values associated with the resistance fluctuations displayed by a resistor in a nonequilibrium stationary state [3]. These results show that when the auto-correlation function displays a non-exponential and non-power-law decay, the distribution of the return times of extreme values still keeps the stretched exponential form observed when long-term correlations [1, 2] are present. Moreover, the value of the stretching exponent is largely independent of the threshold [3]. Thus, stretched exponential distributions cannot be considered an exclusive feature of long-term correlated time series.

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Multivariate Recurrence Plots for Visualizing and Quantifying the Dynamics of Spatially Extended Natural Systems

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Few methods for quantifying the dynamics of temporal processes are readily applicable to spatially extended systems when equations governing the motion are unknown. The objective of this paper is to illustrate how the MRP-RQA (Multivariate Recurrence Plot-Recurrence Quantification Analysis) approach may serve to characterize natural systems driven by both deterministic and stochastic forces. The strength of the MRP-RQA approach resides in its independence from constraining assumptions regarding outliers, noise, stationarity and transients. Its utility is demonstrated by means of two spatiotemporal series (summer and spring datasets) of light intensity variations in an old growth forest ecosystem. Results revealed qualitative differences in homogeneity, transiency, and drift typologies between the MRPs derived from each dataset. RQA estimates of the Kolmogorov entropy supported the idea that mixed chaotic-stochastic dynamics may be more the rule than the exception in mesoscale systems. Advantages and inconveniences of the MRP-RQA approach are also discussed in the general context of environmental monitoring.

Estimation of the Direction of the Coupling by Conditional Probabilities of Recurrence *(Keynote Lecture)*

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We introduce a new method to detect and quantify the asymmetry of the coupling between two interacting systems based on their recurrence properties. This method can detect the direction of the coupling in weakly as well as strongly coupled systems. It even allows detecting the asymmetry of the coupling in the more challenging case of structurally different systems and it is very robust against noise. We also address the problem of detecting the asymmetry of the coupling in passive experiments, i. e., when the strength of the coupling cannot be systematically changed, which is of great relevance for the analysis of experimental time series.

Recurrence Plots (RP) and Recurrence Quantitative Analysis (RQA) Disclose the Dynamical Structure of Human Sleep from its Microstructure *(Poster)*

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Several applications of RP to physiological signals, including electroencephalogram (EEG) signals during NREM and REM sleep stages (sleep macrostructure), have been proposed and have been related to other non-linear analysis parameters such as correlation dimension, fractal dimension and entropy . Up to now, however, a RPs analysis of sleep microstructure has not been performed yet. This include peculiar transient EEG phenomena usually lasting from 0.5 seconds to a few seconds (mainly K complexes and bursts of delta waves, excluding arousals, low frequency components of A phases of Cycling Alternating Pattern (CAP)) that could reveal a pseudo-periodic pattern during sleep deepening. Our preliminary data analyzing sleep microstructure in 8 young healthy subjects showed that the RP method could discriminate: a) attractor-driven oscillation patterns of the transient EEG phenomena during transitions towards deep sleep, visually represented by slow wave sleep (SWS) and expression of EEG synchronization; b) the loss of this attractor-driven oscillations (chaotic oscillations) several seconds before REM phases. This data are consistent with the hypothesis that a subcortical oscillator is not only related with the deepening of NREM sleep, but it has to cease in order to permit the occurrence of REM phase. The potential impact of sleep parametrization based on RP and RQA in physiologic and pathologic conditions is currently under investigation as a tool for detecting subtle or otherwise unrecognizable situations of disturbed sleep.

Speech Analysis Using Recurrence Quantification Analysis

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Current methods of recurrence quantification analysis rely on the use of thresholded plots which remove much of the detailed topological structure from the computed distance matrix. I attempt to explore how the entirety of the distance matrix can be used to investigate the local dynamical structure of a signal. In particular I turn the recurrence paradigm to work on speech analysis and the task of tackling the issue of time/frequency representation. Alternatively this approach can be thought of as a way of studying signal-internal coordination dynamics.

Cross Recurrence Plots in the Analysis of Extreme Ocean Storm Surges

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Serious floods severely impact coastlines and result in damages of infrastructure and fatalities. It is important to identify the return period of the extreme storms and their relationship with surges. In this research, recurrence plot is used as a tool to visualize and analyze the recurrence of states in phase space. The nonlinear relationship analysis between surges and meteorological forcings (winds and air pressure) is investigated and characterized by means of cross recurrence plot and cross recurrence quantification analysis. The North Sea is taken as a case study of this research.

Cardiorespiratory Interaction during Simulated Sleep Apnea Explored by Joint Recurrence Plot Analysis *(Poster)*

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Cardiovascular and respiratory systems are intimately coupled to manage with metabolic needs of the whole organism. They are under control of complex, usually nonlinear, hierarchical, multi-input and multi-output, often common networks of autonomic and central nervous system. Cardiorespiratory synchronization vary in health and disease and its qualitative and quantitative indices could be of prognostic and diagnostic value. Although a number of parameters derived by linear (spectral) and nonlinear (correlation dimension, entropies, recurrence plot) analysis proved to be useful in research and clinical practice, they usually refer to only one or two variables. Multisignal analysis could bring more details of the systems dynamics. To study influence of respiratory pattern on cardiorespiratory coupling, 30 young healthy subjects took part in an experimental procedure consisting of control -C, apnea -A (1 min. voluntary apneas separated by 1 min. spontaneous breathing) and recovery -R period, 20 minutes each. Nonivasively recorded blood pressure (BP, Portapres-2, Holland), respiratory activity - thermistore- (RESP, CardioLab, Poland) and blood oxygen saturation (SPO2, DATEX, Finland) were digitized (Spike-2, CED, England) and saved for further off-line analysis (BEATFAST-Holland, MATLAB-USA). Inter-beat interval (IBI) measured as RR- interval in ECG, systolic (SYS), diastolic (DIAS) arterial blood pressure and RESP entered Joint Recurrence Quantification Analysis (partly CRP Toolbox 5.5 by Norbert Marwan) procedures. A range of recurrence parameters such as recurrence rate (RR), determinism (DET), entropy (ENTR) and trapping time (TT) were calculated for IBI, SYS, DIAS and RESP signals in C, A and R phases. Basing on false nearest neighbor criteria embedding dimension of value 7 was set for joint recurrence analysis. The threshold 0.05 of maximal distance and 12 samples time delay was chosen for all signals. The least affected by experimental procedure was DET which remained within range 0.8-0.9, increasing slightly (maximum 5%) during A. Voluntary apneas decreased RR in all separately analyzed signals from about 0.17 in control to 0.1 during apnea and 0.12 in recovery. The most visible drop of RR could be noticed for IBI and RESP, 35% and 29% respectively. Joint RR was substantially lower (0.025), however it increased 80% and 70% in A and R respectively. Entropy of SYS and DIAS was in the range 2 to 3 increasing 10-15% during A and remaining on the control level during R. For IBI entropy successively decreased in A and R and was opposite for RESP. Joint ENTR increased from 1.7 in C to 2.2 in apnea and 2 in R. Trapping time decreased in IBI signal from 6.3 during control to 4.6 in apnea and recovery. There were no significant change of this parameter for blood pressure and RESP signals. TT determined for joint recurrence matrix was about 3 in C and increased to 5 and 3.9 in A and R respectively. Basing on the above, preliminary results two general conclusions can be formulated:

1. Dynamics of separately analyzed IBI, SYS, DIAS and RESP signals become less periodic during apneic phase whereas their joint recurrence suggests opposite behavior of the whole system at similar level of complexity and higher probability of chaos-chaos transitions.

2. Changes of recurrence parameters following brief chemoreceptor stimulation in young healthy subjects outlast apneic period suggesting prolonged modification of cardiopulmonary control system dynamics.

This work was supported by grant: 1 H01F 037 26 from the Polish Ministry of Higher Education

Anaesthetics Differentially Affect Fluctuations in Haemodynamic Rhythms *(Poster)*

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Introduction: Cardiovascular dynamics in health and disease appear to reflect complex regulatory mechanisms [1], which can be analysed by assaying fluctuations in haemodynamic rhythms. Decreases in haemodynamic fluctuations have been associated with aging and various critical pathologies, e.g. sepsis. Anaesthetics have marked effects on habitual circulatory variables, e.g. arterial pressure and heart rate. We studied the impact of four anaesthetics on haemodynamic fluctuations using recurrence quantification analysis (RQA).

Methods: With approval of the District Governmental Animal Research Committee, anaesthetized and mechanically ventilated foxhounds received subsequently 2 doses of either a volatile anaesthetic (desflurane [DES] at 7.2 and 14.4 Vol.% or sevoflurane [SEV] at 2.3 and 4.6 Vol.%) or an intravenous anaesthetic (propofol [PRO] at 10 and 20 mg/kg/h or methohexital [MET] at 20 and 40 mg/kg/h). Systolic arterial pressure (SAP) and RR interval (RRI; reciprocal of heart rate) time series were analysed using RQA as previously described [2]. Statistics: Medians (Range), ANOVA on Ranks, Dunn's post hoc test, $p < 0.05$.

Results: SAP was highest with MET, while RRI were largest with PRO. Fluctuations in SAP and RRI time series were significantly higher with PRO than with other anaesthetics: Recurrence rate (REC), determinism (DET) and entropy (ENT) were lowest and divergence (DIV) was highest in the PRO group independently of the applied dose of anaesthetic. Among DES, SEV and MET groups there were no intergroup differences regarding RQA measures. Correlations were significant for SAP vs. REC (SAP) as well as for RRI vs. DET (RRI), ENT (RRI) and DIV (RRI) in the MET group, and for SAP vs. REC (SAP), DET (SAP), DIV (SAP) and ENT (SAP) in the PRO group.

Conclusion: Anaesthetics have a bold impact on fluctuations in haemodynamic rhythms, which cannot be attributed exclusively to changes in heart rate or systemic blood pressure level. These effects are substance-specific, with PRO preserving haemodynamic fluctuations on a significantly higher level than other anaesthetics. If our results apply to humans, the choice of anaesthetic agents may be one factor determining patients haemodynamic fluctuations.

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Recurrence Quantification Analysis of Meteorological Time Series *(Poster)*

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Introduction: Climatic processes are among the most complex phenomena we know. Since deterministic elements mingle with stochastic and chaotic dynamics, the habitual linear time series analysis techniques are bound to fail in completely describing meteorological processes. Recurrence quantification analysis (RQA) [1] has proved to be a robust method for the analysis of time series and does not require any assumptions about underlying dynamics or statistical distributions. Therefore it might be an ideal tool to investigate climatological dynamics. We performed a RQA on meteorological data of the passed century.

Methods: Data of four German meteorological stations were provided by the German Meteorological Service. Time series of daily measurements of mean air pressure PM, mean temperature TMK, maximum temperature TXK, maximum temperature changes TRK, mean vapour pressure VPM and mean wind force FMK from 1876 to 2006 were divided into overlapping windows of 4 years, with a lag of 1 year among each epoch. For every window the arithmetic mean AM and 7 RQA variables (recurrence rate REC, determinism DET, longest diagonal line MAXL, entropy ENT, trend TND, laminarity LAM and trapping time TT) were computed and transformed into secondary time series. Linear regression, the autocorrelation function ACF, power spectra and RQA characteristics of these time series were calculated.

Statistics: Medians (Range), ANOVA on Ranks, Tukey's post hoc test, $p < 0.05$.

Results: No significant overall differences were found among the four meteorological stations. Among the studied six meteorological variables, RQA values were significantly high for the FMK time series while the remaining five variables did not show consistent intergroup differences. However, significant differences were detected among the eight characteristics computed for each window: The AM time series yielded higher slopes of the regression line than the RQA variables. First-order autocorrelation functions were significantly different from zero for the AM time series and all RQA variables but the TND series. According to the power spectrum analysis, the temporal evolution of the latter could be modelled by a white noise process while the remaining RQA variables fitted with a first-order autoregressive process. The AM time series did not correspond well to any of the tested dynamics and yielded uniformly higher RQA values than the remaining secondary time series.

Conclusion: For the analysis of meteorological data sets, RQA has been shown to be a feasible and valuable tool, capable of revealing new features which remain hidden to standard methods of time series analysis. Due to its many advantages it may establish as a crucial component in the analysis of complex real world phenomena like atmospheric dynamics. Further studies are necessary to fully understand the behaviour of RQA variables (e. g. dependence on embedding dimension etc.) and to optimise their interpretation.

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Recurrence Quantification Analysis and State Space Divergence Reconstruction for Financial Time Series Analysis

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The application of Recurrence Quantification Analysis (RQA) and State space divergence reconstruction for the analysis of financial time series in terms of cross-correlation and forecasting is illustrated using high-frequency time series and random heavy tailed data sets. The results indicate that these techniques, able to deal with non-stationarity in the time series, may contribute to the understanding of the complex dynamics hidden in financial markets. The results demonstrate that financial time series are highly correlated. Finally, an on-line trading strategy is illustrated and the results shown using high frequency foreign exchange time series.

20 Years of Recurrence Plots
(Anniversary Talk)

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In this talk I will give a personal account of my view on recurrence plots. I will outline the importance of recurrences in the framework of dynamical systems and address the question why recurrence plots are such a powerful tool in time series analysis.

In spite of the huge progress in the understanding of structures found in recurrence plots, many questions remain open. I will point out some of these issues, and show why there is still much to be learnt from recurrence plots.

Complexity Analysis of RNA Sequences with Recurrence Plots *(Poster)*

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We employed recurrence plots to analyze correlations structure of RNA sequences. It is found that a complex correlations among distinct sites on a set of RNA sequences. It indicates important structural information of the sequences.

Recurrence Quantification Analysis as a Method for the Detection of Environmental Thresholds

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A non-linear time series analysis technique, recurrence quantification analysis (RQA) is proposed in this work for the detection of environmental thresholds. Its application is illustrated for three case studies: lake eutrophication by excessive phosphorous, the regime shift that occurred in Ringkøbing Fjord when water exchange with the North Sea was modified and the oxygen dynamics in a Mediterranean coastal lagoon (Sacca di Goro). The results show that RQA is robust against high noise levels (up to 100%) and may be easily implemented on-line. The main drawbacks are the relatively high number of data points required and the need of a constant sampling with no gaps, which may be problematic for some environmental time series.

Laminar Recurrences, Maxline, Unstable Singularities and Biological Dynamics
(Keynote Lecture)

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Recurrence quantification analysis can reveal subtle aspects of dynamics not easily appreciated by other methods such as the Fourier transform. Laminarity and maxline are two RQA variables that can demonstrate the presence of unstable singularities which are often found in biological dynamics. Examples are presented and their implications are discussed relative to deterministic dynamics and stochastic processes.

Recurrence Quantitative Analysis of Stick Slip Acoustic Emission Dynamics under Small Periodic Electromagnetic Forcing

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As known dynamical properties of complex systems are essentially changed under small external influence. In recent times it was shown that small, comparing to natural forces, anthropogenic affects may influence dynamical properties of local seismic process. At the same time, real data sets often are too short and incomplete to draw unambiguous conclusion on related complex dynamics and especially on small quantitative changes. Based on the mentioned findings on the dynamical effects of small influences, in present research we aimed to carry out quantitative analysis of such changes in laboratory model data. Laboratory set up contained two samples of roughly finished basalt. The lower sample was fixed and upper one was pulled with constant speed. Data sets have been obtained during stick-slip experiments under or without periodic mechanical or electromagnetic (EM) forcing, which simulates the external periodic influence. Slip events were recorded as acoustic emission bursts. In order to test possible dynamical changes of acoustic emission data, recurrence quantification analysis (RQA) method, as most appropriate for qualitative and quantitative testing of high dimensional process was used. It was shown that at a constant pulling force, when the intensity of normal to slip surface periodic EM field increases, main RQA characteristic increase under conditions close to phase synchronization. Moreover recurrent patterns of series of time intervals between consecutive AE onsets and AE maximums increases. This means that increases the extent of regularity in time distribution of acoustic emission. It is important that at the same time amount of large AE events decreases.

Low-dimensional Dynamics in Magnetized Plasma Turbulence *(Poster)*

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We analyze electrostatic probe data from a toroidal magnetized plasma configuration suitable for studies of low-frequency gradient-driven instabilities [1]. These instabilities give rise to field-aligned convection rolls analogous to Rayleigh-Benard cells in neutral fluids, and may theoretically develop similar routes to chaos [2].

In a real plasma system it is not likely that one will observe "clean low-dimensional chaos: the typical situation is that high-dimensional turbulent dynamics dominate the smaller scales, while lower dimensional dynamics govern the global scale of the system. By low-pass filtering the original data we extract the component which we analyze by implementing mean-field dimension analysis [3]. For the given level of averaging, the mean-field dimension determines the minimum dimension of the embedding space in which the averaged dynamical system approaches the actual dynamics.

We observe low-dimensionality, but this could originate from either low-dimensional chaos or from quasi-periodicity. Therefore, we apply recurrence plot analysis [4], whose analysis provides evidence of low dimensional chaos, in agreement with theoretical predictions [2].

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Recurrence Plots and Quasiperiodicity

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Quasiperiodicity is the simplest form of dynamics exhibiting nontrivial recurrence with low complexity. Recurrence Plots of quasiperiodic motion exhibit intricate line structures with non-equal distances, but a complete systematic description of them is still lacking. In this talk, we analyze quasiperiodic dynamics in the context of RPs and discuss the relationship to the rather old, but little-known Slater's theorem. Based on this theorem, we propose a method to distinguish quasiperiodic from chaotic dynamics in rather short time series.In Hamiltonian systems, a typical chaotic trajectory spends a long time of stay near the boarder of the stable islands, showing almost regular motion, which is called stickiness. RPs can easily visualize the difference between quasiperiodic and such weak chaotic orbits. We will see that Recurrence Quantification Analysis can be used to characterize the stickiness property, which agrees well with the results in the literature.

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