Potsdam
September 22-24, 2005

1st RECURRENCE PLOT WORKSHOP

Universität Potsdam

Programme

RECURRENCE PLOT WORKSHOP

Satellite Meeting of the 13th International IEEE Workshop

on Nonlinear Dynamics of Electronic Systems (NDES2005)

Potsdam, September 22nd–24th, 2005

Universität Potsdam

Scientific and Organisational Committee

Norbert Marwan[1]
M. Carmen Romano[1]
Marco Thiel[1]
Joseph Zbilut[2]
Jürgen Kurths[1]

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Aims

This recurrence plot workshop is the first meeting having recurrence plot methods and applications as exclusive subjects. The aim is to bring together the community working on or using recurrence plot based methods, to share knowledge about recurrence plots and to present new developments and theoretical aspects. Moreover, this meeting will fathom future potentials of recurrence plots in investigating spatio-temporal data, image analysis, statistical tests etc. The meeting will push the publicity of recurrence plots in the scientific community and highly encourage scientists to develop new recurrence plot based techniques and to apply them in various scientific fields.

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 software for calculation of dynamical invariants. A comprehensive RQA, study of interrelations, synchronisations or dynamical invariants can be provided.

Note: The practical workshop will take place at *Campus Golm*

Internet Access

During the NDES meeting and the RP workshop, access to the Internet will be available in the PC Pool (Room 4.23) in building 19 in the lunch breaks.

Social Event

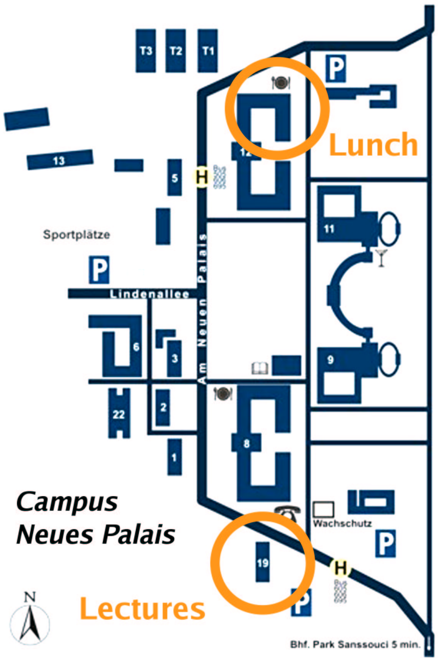
At Friday evening a barbecue will be prepared besides the Instituts building. Everyone is invited to participate, but has to register for this event on the registration desk.

Location

The workshop takes place in Potsdam, a former residencial site of the prussians emperors. The university campus *Neues Palais* is partly located in the former royal palace, directly at the famous *Sanssouci Park*.

Lectures

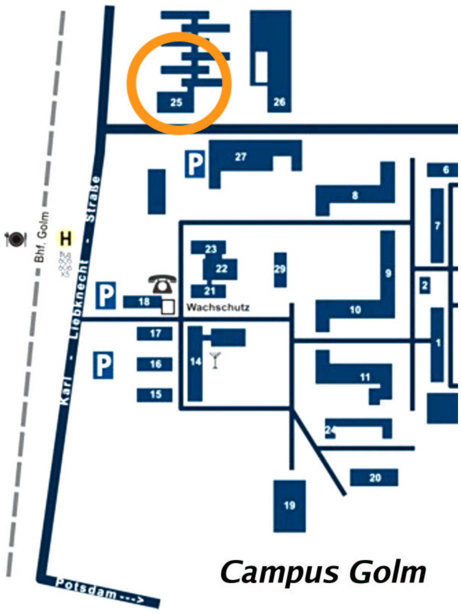
University of Potsdam, *Campus Neues Palais*, Building 19, Room 4.15



Practical Workshop

University of Potsdam, *Campus Golm*, Building 25, PC Pools/ CIP Pools 1a, 1b and 2a

There is a very good bus connection between *Campus Neues Palais* and *Campus Golm* going every ten minutes. Take bus number 606 (direct connection) or 605 (small detour, 5 min. longer than bus 606) from bus station *Lindenallee* to bus station *Golm Bahnhof*.



Bus timetable (Hotel ▷ University)

Potsdam, Sonnenlandstr. ▸ Potsdam, Neues Palais

Ⓗ Potsdam, Sonnenlandstr. Gültig von 18.09.2005 bis 25.09.2005

Fahrt	Dauer	Richtung
Bus 695	ca. 4 Min.	S Potsdam Hauptbahnhof
Bus N18	ca. 3 Min.	Golm (PM), Bahnhof

⏲	Kateg.	Montag - Freitag	Samstag	Sonntag
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02	BUS	00	00	00
03	BUS	00	00	00
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06	BUS	01 21 41	01 21 41	01 21 41
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21	BUS	01	01	01

Zeichenerklärung
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Alle Angaben ohne Gewähr. Erstellt am 12.09.05 um 15:37.
Informationen zum Kurzstreckentarif erhalten Sie an der Haltestelle oder beim Fahrer

Bus timetable (University ▷ Hotel)

BUS **Potsdam, Neues Palais ▸ Potsdam, Sonnenlandstr.**

Ⓗ **Potsdam, Neues Palais** Gültig von 18.09.2005 bis 25.09.2005

Fahrt	Dauer	Richtung
Bus 695	ca. 3 Min.	Potsdam, Bahnhof Pirschheide
Bus N18	ca. 4 Min.	S Potsdam Hauptbahnhof

⏲	Kateg.	Montag - Freitag	Samstag	Sonntag
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Alle Angaben ohne Gewähr. Erstellt am 12.09.05 um 15:38.
Informationen zum Kurzstreckentarif erhalten Sie an der Haltestelle oder beim Fahrer

Bus timetable (Campus Neues Palais ▷ Campus Golm)

BUS **Potsdam, Lindenallee ▸ Golm (PM), Bahnhof**

Ⓗ **Potsdam, Lindenallee** Gültig von 23.09.2005 bis 23.09.2005

Fahrt	Dauer	Richtung
Bus 605	ca. 11 Min.	Golm (PM), Bahnhof
Bus 606	ca. 10 Min.	Golm (PM), Max-Planck-Campus
Bus N18	ca. 7 Min.	Golm (PM), Bahnhof

◷	Kateg.	Montag - Freitag
04	BUS	04 49
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08	BUS	02 11[1] 22 31 42 51
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Richtungen:
1 = Neu Töplitz, Wendeplatz

Alle Angaben ohne Gewähr. Erstellt am 12.09.05 um 16:41.
Informationen zum Kurzstreckentarif erhalten Sie an der Haltestelle oder beim Fahrer

Bus timetable (Campus Golm ▷ Campus Neues Palais)

BUS Golm (PM), Bahnhof ▸ Potsdam, Neues Palais

Ⓗ **Golm (PM), Bahnhof**

Gültig von 23.09.2005 bis 23.09.2005

Fahrt	Dauer	Richtung
Bus 605	ca. 11 Min.	S Potsdam Hauptbahnhof
Bus 606	ca. 10 - 16 Min.	S Potsdam Hauptbahnhof
Bus N18	ca. 8 Min.	S Potsdam Hauptbahnhof

🕒	Kateg.	Montag - Freitag
05	BUS	12 45
06	BUS	05 15 25 45 55
07	BUS	05 14 15 25 35 45 55
08	BUS	05 15 25 35 45 55
09	BUS	05 16 25 35 45 55
10	BUS	05 15 25 35 45 55
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18	BUS	05 13 25 35 45 55
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21	BUS	41 52
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01	BUS	46
02	BUS	46
03	BUS	46
04	BUS	40

Alle Angaben ohne Gewähr. Erstellt am 12.09.05 um 15:36.
Informationen zum Kurzstreckentarif erhalten Sie an der Haltestelle oder beim Fahrer

VBB

Programme

Thursday, September 22nd

13:30 Registration

Introduction and Theory

14:15 **M. Thiel**: Welcome & On Recurrences

14:30 **J. P. Zbilut**:
Recurrence Quantification Analysis: Introduction and Historical Context

15:00 **Ch. L. Webber Jr.**:
Recurrence Quantifications: Feature Extractions from Recurrence Plots

15:30 *Coffee break*

16:00 **M. Thiel**, M. C. Romano, J. Kurths:
Dynamical Invariants and Surrogates from Recurrence Plots

16:30 **R. L. Machete**:
Coping With Change

17:00 **Chr. Bandt**:
Order Patterns in High-Dimensional Time Series

17:30 **N. Marwan**, J. Kurths:
Line Structures in Recurrence Plots

17:50 **K. Urbanowicz**, J. A. Hołyst:
Anti-Deterministic Data That are More Unpredictable Than Noise

Friday, September 23rd

Applications

8:30 **A. Facchini**, H. Kantz, N. Marchettini, E. Tiezzi:
Curved Patterns in Recurrence Plots

8:50 **A. Colosimo**, G. Zimatore:
Individual and Pathological Features in Otoacoustic Emissions Identified by Recurrence Quantification Analysis

9:15 **N. Wessel**, N. Marwan, A. Schirdewan, J. Kurths:
Recurrence Plot Analysis of Heart Rate Variability Before the Onset of Ventricular Tachycardia

9:40 **L. Santos Montalbán**, P. Henttu, R. Piché:
Recurrence Plot Analysis of Electrochemical Noise Data

10:00 *Coffee break*

10:30 **Poster Session**

11:20 **N. Zolotova**:
Recurrence Plot Analysis of Climatic and Sunspot Time Series

11:40 M. Trauth, **N. Marwan**, J. Kurths:
Comparing Modern and Pleistocene ENSO-Like Influences in NW Argentina Using Cross Recurrence Plot Analysis

12:00 *Lunch*

Workshop
(the workshop will take place in PC pools/ CIP pools 1a, 1b and 2a at Campus Golm)

13:30 **N. Marwan**:
Introduction in CRP Toolbox
Ch. L. Webber Jr.:
Usage of RQA Software
M. C. Romano:
C Programmes for Dynamical Invariants

14:00 (til 18:00) *Demonstrations in separate groups:*
A CRP Toolbox
B RQA Software
C C Programmes for Dynamical Invariants

18:00 Social event *Barbecue at Physics Building (Campus Neues Palais)*

Saturday, September 24th

New Developments

8:30 **M. C. Romano**, M. Thiel, J. Kurths:
Synchronization Analysis of Fixational Eye Movements by Means of Recurrence Plots

9:00	**E. Macau**: Chaos Synchronization Based Parameter Estimation
9:30	**A. Groth**: Visualization of Bivariate Coupling by Order Recurrence Plots
10:00	**M. Furman**: Dynamical Determinism: a Fast Algorithm for Calculating Determinism
10:30	*Coffee break*
11:00	**Sh. Horai**, T. Yamada, K. Aihara: Visualizing Nonlinear Determinism by Iso-Directional Recurrence Plots
11:30	**R. Viana**, D. B. Vasconcelos, J. Kurths: Spatial Recurrence Plots in Snapshot Patterns of Coupled Map Lattices
12:00	**N. Marwan**, P. Saparin, J. Kurths: Recurrence Plot Extension for 2D Spatial Data
12:30	Round Table Discussion: Perspectives
13:00	*Lunch*

Poster

Poster 1 **J. P. Zbilut**, T. Scheibel, D. Hümmerich, Ch. L. Webber Jr., M. Colafranceschi, A. Giuliani:
Spatial Stochastic Resonance in Spider Silk as Detected by Recurrence Analysis

Poster 2 **J.-F. Casties**, D. Mottet, S. Ramdani:
Recurrence Quantification Analysis of Heart Rate Variability During a Constant Load Exercise

Poster 3 **K. Becker**, M. Eder, et al.:
Evidence for a Consistent Neurophysiological Indicator of General Anesthesia

Poster 4 **K. Chandrasekaran**, M. Thiel, M. C. Romano, J. Kurths:
Understanding Brain Dynamics by Recurrence Plots

Poster 5 **N. Marwan**, A. Groth:
Improved Recurrence Quantification Analysis for the Investigation of ERP Data

Poster 6 **A. Groth**:
Recurrence Analysis on Ordinal Scale

Poster 7 **N. Marwan**, N. R. Nowaczyk, M. Thiel, J. Kurths:
Re-Alignment of Geological Time Series Using the Cross Recurrence Plot Toolbox

Poster 8 **M. C. Romano**, D. Pazo, M. Thiel, J. Kurths:
Detection of Unstable Tori by Means of Recurrence Plots

Poster 9 **Y. Zou**, M. Thiel, M. C. Romano, J. Kurths:
Shrimp Structure and Associated Dynamics in Parametrically Excited Oscillators

Timetable

Time	Thursday	Friday	Saturday
8:30		Applications I	New
9:00			Developments I
9:30			
10:00		*Coffee Break*	
10:30		Poster Session	*Coffee Break*
11:00			New
11:20		Applications II	Developments II
12:00		*Lunch*	
12:30			Discussion
13:00			
13:30	Registration	Workshop	
14:00	Opening	*(Campus Golm)*	
14:30	Introduction		
15:00			
15:30			
16:00	*Coffee Break*		
16:30	Theory		
17:00			
17:30			
18:00		Social Event	
18:30		*Barbecue*	
19:00			

Abstracts

Order Patterns in High-Dimensional Time Series

Christoph Bandt

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To understand collective behavior and synchronization of multi-channel time series, multivariate order patterns are used to define correlation and entropy parameters. Results will be demonstrated for evoked EEG data.

Evidence for a Consistent Neurophysiological Indicator of General Anesthesia (Poster)

Klaus Becker[1], **Matthias Eder**[2], **R. Marsch**[1], **A. Ranft**[2,3], **W. Jacob**[1], **E. Kochs**[3], **W. Zieglgänsberger**[2], **H. U. Dodt**[2]; **C. T. Wotjak**[1]

[1] *Neuronal Plasticity Group, Max Planck Institute of Psychiatry, Munich, Germany*

[2] *Clinical Neuropharmacology, Max Planck Institute of Psychiatry, Munich, Germany*

[3] *Department of Anesthesiology, Klinikum rechts der Isar, Munich, Germany*

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Is there a consistent neurophysiological indicator of general anesthesia independent from the anesthetic used? To address this question, we studied the effects of the general anesthetics isoflurane, propofol, and ketamine on the electrical activity recorded in vivo directly from the hippocampal CA1 region of adult mice. The electrical signals obtained were analyzed with respect to gamma activity (20-70 Hz) and a lower frequency band (1-19 Hz). Consistent with a dampened neuronal network activity during general anesthesia, isoflurane decreased the spectral power of both frequency bands. Intriguingly, both propofol and ketamine induced the opposite effect. This observation made it highly unlikely to find a consistent neurophysiological indicator of general anesthesia by this classical approach. However, as previously proposed, such an indicator might be unraveled by non-linear signal analyses. Therefore, we applied windowed recurrence quantification analysis (RQA) to recording traces. RQA sensitively detects the amount of the complexity of time series. We revealed a prominent decrease in the number of "up states" of complexity (USCs) common to all three anesthetics under investigation. This phenomenon presumably reflect alterations in the temporal correlations between different patterns of electrical activity, independent from a diminished or enhanced spectral power. It may be speculated that USCs mirror episodes of information processing during consciousness. Therefore, a decrease in the rate of USCs could serve as a general indicator of anesthetic-induced unconsciousness.

Supported by the SFB 391.

Recurrence Quantification Analysis of Heart Rate Variability During a Constant Load Exercise (Poster)

Jean-François Casties, Denis Mottet, Sofiane Ramdani

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At rest, Heart Rate Variability (HRV) shows nonlinear properties. In this way, in addition to traditional analysis (temporal and spectral), it is appropriate to use nonlinear methods on HRV time series. Among these methods some are devoted to the estimation of the invariants of the dynamics such as Largest Lyapunov Exponent (LLE) or Embedding Dimension (ED). Other methods like Recurrence Quantification Analysis (RQA) also allows the detection of transitions between chaotic behaviours. In this way, RQA seems particularly appropriate to analyse HRV time series: this tool would be able to anticipate Ventricular Tachycardia [1].

During exercise, traditional analyses appear to be limited, showing only a large decrease of all the parameters. Nonlinear analyses demonstrate that the structure of HRV has a lower complexity during exercise compared to rest, but the effect of time duration is unknown. Thus, the aim of this study was to analyse the HRV behaviour and its evolution with length of exercise. In addition to usual nonlinear analysis (LLE, ED), RQA parameters were calculated in order to detect even subtle changes in HRV.

LLE and classical RQA variables decreased between rest and exercise, and did not change significantly during exercise. Moreover, there was no effect on ED. Most of RQA variables showed a decrease between rest and exercise, except the % determinism. These results show that HRV behaviour changed from rest to exercise, but still had nonlinear dynamics.

LLE and ED were unable to detect changes during exercise. On the contrary, recent RQA complexity measures, such as Laminarity (Lam) and maximal length of vertical structures (Vmax), decreased with time duration. This latter result shows that, even if HRV remains nonlinear, changes in the complexity of the system occur when exercise lasts. Undetectable by LLE ore ED, these changes could involve chaotic to chaotic transitions. Their physiological signification remains to be elucidated, but changes in synchronisation between heart, ventilation and locomotion might play an important part in these changes.

References

[1] Marwan, N., Wessel, N., Meyerfeldt, U., Schirdewan, A., Kurths, J.: Recurrence Plot Based Measures of Complexity and its Application to Heart Rate Variability Data, Phys. Rev. E **66**(2), 026702 (2002).

Understanding Brain Dynamics by Recurrence Plots (Poster)

Komalapriya Chandrasekaran, Marco Thiel, Maria Carmen Romano, Jürgen Kurths

University of Potsdam, Nonlinear Dynamics Group, Potsdam, Germany
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Understanding the transitions in brain dynamics from normal state to a seizure based on EEG recordings is a challenging task in epileptology. Recurrence Plots could be an appropriate tool for the characterization of the transitions in brain activity from baseline to epileptic seizures as they can handle the following problems of the EEG recordings: (i) high dimensionality, (ii) non-stationarity and (iii) observational noise. First results suggest that some RQA measures have the potential to discriminate between the inter-ictal, pre-ictal and the ictal phases of the brain. Careful application of the recurrence analysis could give promising results for the prediction of seizures and to gain new insights into the dynamics of epileptic seizures.

Individual and Pathological Features in Otoacoustic Emissions Identified by Recurrence Quantification Analysis.

Alfredo Colosimo, Giovanna Zimatore

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A study of click-evoked otoacoustic emissions (CEOAEs) elicited at stimulation intensities from 35 to 80 dB can be easily carried out by recurrence quantification analysis on signals from both normal and hearing-impaired subjects, and a number of subject-dependent features may be revealed in the form of different maximal levels of determinism.

The efficacy of RQA in extracting physiological information from otoacoustic emissions at fixed stimulation intensity was previously demonstrated [1, 2]. More recently [3], we addressed the goal of investigating the effect of varying stimulus intensity on the dynamic features of CEOAEs. Our specific aim was, for both normal and hearing-impaired subjects, to provide clues concerning i) the discrimination between subject- dependent and population-dependent features, and ii) the identification of morphoanatomic and functional factors contributing to normal and altered responses. For the normal hearing subjects, we present data on the deterministic features of CEOAEs, which, above a given threshold of stimulation intensity, confirmed significant differences among individuals in terms of the maximal attainable amount of signal autocorrelation measured by determinism. As for hearing-impaired subjects, in particular, we show that the measure of determinism is actually able to discriminate between conductive hearing losses (CHL) and sensorineural hearing losses (SHL), corresponding to middle and inner ear disorders, respectively. A general conclusion of our study is that determinism, as measured by RQA, can faithfully quantify the dynamic features of CEOAEs in a somewhat unexpectedly broad range of conditions. More specifically, if SHL and CHL can, in principle, be discriminated also by standard clinical indicators, the information on the signal dynamics extracted through the RQA variables would appear more reliable because it is less affected by noise and/or possible instrumental flaws over a wide range of stimulation intensities, and it is solidly rooted on the global morphoanatomic features of the auditory system.

Very recently, the conclusions obtained by sistematic use of RQA variables, have been confirmed by an electric ear model used to study the individual variability of CEOAEs. The obtained results show that the simulated signal is not only able to reproduce the typical features of the otoacustic emissions measured in normal hearing subjects, but also to discriminate among different hearing losses.

References

[1] Zimatore, G., Giuliani, A., Parlapiano, C., Grisanti, G. and Colosimo A.: Revealing deterministic structures in click-evoked otoacustic emissions, J. Appl. Physiol. **88**, 1431-1437 (2000).

[2] Zimatore, G., Giuliani, A., Hatzopoulos, S. and Colosimo, A.: Comparison of the transient otoacustic emission (TEOAE), responses from neonatal and adult ears, J. Appl. Physiol. **92**, 2521-2528 (2002).

[3] Zimatore, G., Giuliani, A., Hatzopoulos, S., Martini, A. and Colosimo, A.: Otoacoustic emissions at different click intensities: invariant and subject-dependent features, J. Appl. Physiol. **95**, 2299-2305 (2003).

Curved Patterns in Recurrence Plots

Angelo Facchini[1]**, Holger Kantz**[2]**, Nadia Marchettini**[1]**, Enzo Tiezzi**[1]

[1] *Siena University, Chemical and Biosystems Sciences, Siena, Italy*

[2] *Max Planck Institute for the Physics of Complex Systems, Dresden, Germany*

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We present the results of a recurrence plot based analysis of the calls of the gibbons *Hylobates lar* and *Nomascus concolor*. Both Gibbons emit vocalizations characterized by a slight linear increase of the frequency plus modulations.

The spectrograms of the two calls do not show particular patterns: the one from *Nomascus concolor* looks like a pure sinusoid, while in the one from *Hylobates lar* a slight sinusoidal frequency modulation is present.

In contrast to this, the RP of their calls show characteristic macro-patterns, showing the coexistence of two time scales in the signal. The first is directly related to the main frequency of the sound emission while the second, much lower, produces hyperbolic, circular and gapped patterns in the textures of the RPs. In particular, in the RP of the *Nomascus concolor* gibbon are present the hyperbolic patterns, showing a macro frequency that increases of about four times from the beginning to the end of the signal. More complicated are the patterns of the *Hylobates lar* gibbon, which present closed curved macro-structures and circular rings formed by gaps in the texture of one otherwise periodic RP.

The same effects are shown in the RP of slightly frequency modulated sinusoids, which resemble accurately the natural calls.

The recurrence plot acts as a *magnifying glass* for non-stationary signals involving both phase and frequency shifts otherwise invisible with the standard methods based on spectrograms. We think that the origin of this effect lies in the intrinsic phase error introduced by the sampling.

Dynamical Determinism: a Fast Algorithm for Calculating Determinism

Michael Furman

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Determinism is a robust method used in RQA to elucidate phase recurrence in temporal series and is typically generated over a fixed temporal range between two signals. Limited in scope due to the prohibitive computation time $T(n) \in O(n^2)$ (i.e., time is n^2 bound), the implementation of the Determinism measure can be modified to approach $T(n) \in O(n \log n)$ for computing an n-point Determinism vector or single measures over very long time series.

The method emulates the result of sliding a window of width w and introduces a temporal dynamic to the Determinism measure, allowing resolution and structure to be probed within time series through variable window sizes.

This method can also be used on very long time series because each time delay constant ($x - y = C$) is computed only once, and the resulting line lengths from the differences are summed into a master histogram of length n. Thus only n or $2n$ (depending on whether identical waveforms are used) subtractions are made, and each difference computed only once. Furthermore, since this computation is done on a line-by-line basis, this method lends itself to further speedup and optimization through parallel computing.

Specifics of the algorithm will be discussed along with a C program implementation.

Visualization of Bivariate Coupling by Order Recurrence Plots

Andreas Groth

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We introduce a new method to visualize dependencies between two time series applying the concept of cross recurrence plots (CRPs) [1, 2] to the local ordinal structure. Instead of using the actual values of a time series $\{x(t)\}_t$ we only analyze whether $x(t) < x(t+\vartheta)$ or $x(t) > x(t+\vartheta)$ (Tied ranks $x(t) = x(t+\vartheta)$ are assumed to be rare). The components in a delay embedding $(x(t), x(t+\vartheta), \ldots, x(t+(D-1)\,\vartheta))$ can form $D!$ different patterns concerning the order of their values. The sequence of patterns gives a new symbolic time series $\{\pi_x(t)\}_t$, where we denote $\pi_x(t)$ as *order patterns*. With this symbolic dynamics a complexity measure was already proposed [3] and successfully applied to epileptic seizure detection [4]. Moreover, a distance between time series was introduced to study similarities and dissimilarities between EEG channels [5]. Following the idea of CRPs we introduce the *order recurrence plots*

$$\mathbf{R}(t,t') = \begin{cases} 1 & : \quad \pi_x(t) = \pi_y(t') \\ 0 & : \quad \text{otherwise.} \end{cases} \tag{1}$$

Similar to the CRPs conclusions about the underlying systems can be drawn from structures such as "lines". This plot represents a robust visualization tool, which is invariant with respect to low-frequency trends and monotonic transformations of the amplitudes. We derive a measure of the coupling strength. Connections to the instantaneous phase and the determination of phase coupling are shown.

References

[1] Zbilut, J. P., Giuliani, A. and Webber Jr., C. L.: Detecting deterministic signals in exceptionally noisy environments using cross-recurrence quantification, Phys. Lett. A **246**(1-2), 122-128 (1998).

[2] Marwan, N., Kurths, J.: Nonlinear analysis of bivarite data with cross recurrence plots, Phys. Lett. A **302**(5-6), 299-307 (2002).

[3] Bandt, C., Pompe, B.: Permutation entropy – a complexity measure for time series, Phys. Rev. Lett. **88**, 174102 (2002).

[4] Cao, Y., Tung, W., Gao, J. B., Protopopescu, V. A., Hively, L. M.: Detecting dynamical changes in time series using the permutation entropy, Phys. Rev. E **70**, 046217 (2004).

[5] Keller, K., Wittfeld, K.: Distances of time series components by means of symbolic dynamics, Int. J. Bif. Chaos **14**, 693-703 (2004).

Recurrence Analysis on Ordinal Scale (Poster)

Andreas Groth

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We present recent methods of ordinal time series analysis. In the analysis on ordinal level we do not use the actual values x_t, we only need to know whether $x_t < x_s$ or $x_t > x_s$. In general we study a set of D values $x_t, x_{t+\vartheta_1}, \ldots, x_{t+\vartheta_{D-1}}$, called order patterns. Here we consider two special versions. We start with univariate time series and the analysis of return times. A common definition of a return (recurrence) time is given by $\|x_t - x_s\| \leq \Delta_t$ and a visualization tool are the recurrence plots [1]. In the ordinal analysis we have no metric $\|\cdot\|$, however we give a reasonable definition of recurrence on ordinal scale. This idea is illustrated in an application to fundamental period estimation in speech signals. Next, on bivariate time series we introduce a tool to visualize coupling similar to the cross recurrence plots [2, 3]. We show connections between order patterns and an instantaneous phase and demonstrate the ability to detect phase synchronization.

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Visualizing Nonlinear Determinism by Iso-Directional Recurrence Plots

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Nonlinear deterministic systems can exhibit complex unpredictable behaviors. As tools for analyzing nonlinear determinism of such complex time series, we propose the Iso-directional Recurrence Plots (IDRP) and related methods. The proposed methods represent vectors on orbits similarly to Recurrence Plots(RP), and can be combined with original RP to visualize the characteristics of the vectors that are neighboring and moving in similar directions. We apply the proposed methods to time series from mathematical models as well as to some observed data, and demonstrate the ability of qualitative and quantitative analysis of nonlinear determinism.

Chaos Synchronization Based Parameter Estimation

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We present a new parameter estimation procedure for nonlinear systems. Such technique is based on the synchronization between the model and the system whose unknown parameter is wanted. Synchronization is accomplished by controlling the model as to make it follow the system. We use geometric nonlinear control techniques to design the control system. As an example, this procedure is used to estimate a parameter of the Lorenz system.

Coping With Change

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An aspect of prediction not well understood is the prediction of systems undergoing change in their dynamics. We investigate the prediction of a nonlinear circuit undergoing forcing in temperature. The use of recurrence plots and nonlinear prediction to detect dynamical changes due to temperature changes “are assessed”. We explore some ways of coping with dynamical changes so as to produce better nonlinear predictions.

Improved Recurrence Quantification Analysis for the Investigation of ERP Data (Poster)

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Recent applications of recurrence quantification analysis on EEG data have emphasized the potential of investigation event related potentials on a single trial base. With an innovative modification of recurrence plots, based on rank order structures in the data, the recurrence quantification analysis can be further improved. We present new results using order pattern recurrence plots applied on data of event related potentials and the found improvement in comparison with the common recurrence plots.

Line Structures in Recurrence Plots

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Recurrence plots exhibit line structures which represent typical behaviour of the investigated system. The local slope of these line structures is connected with a specific transformation of the time scales of different segments of the phase-space trajectory. This provides us a better understanding of the structures occuring in recurrence plots. The relationship between the time-scales and line structures are of practical importance in cross recurrence plots. Using this relationship within cross recurrence plots, the time-scales of differently sampled or time-transformed measurements can be adjusted. An application to geophysical measurements illustrates the capability of this method for the adjustment of time-scales in different measurements.

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Re-Alignment of Geological Time Series Using the Cross Recurrence Plot Toolbox (Poster)

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The alignment of the time scales of geological data series to a geological reference time series is of major interest in many investigations, e. g., geophysical borehole data should be correlated to a given data series whose time scale is known in order to achieve an age-depth function or the sedimentation rate for the borehole data. Instead of using the "wiggle matching" by eye, we present the application of cross recurrence plots for such tasks. Using this method, the synchronization and time-rescaling of geological data to a given time scale is much easier, objective and faster than by hand. The application of this method to the rock magnetic data of two different sediment cores from the Makarov Basin (central Arctic Ocean) adjusts them to each other, and makes them comparable. This procedure was perfomed using the CRP toolbox.

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Recurrence Plot Extension for 2D Spatial Data

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Classically introduced recurrence plots (RPs) can only be applied to one-dimensional data like phase space vectors and time series. We develop an extended and generalized RP approach which enables us to analyze spatial (higher-dimensional) data regarding recurrent structures. Resulting RPs have higher dimensions (e.g. 4). Hence, the measures used to evaluate classic RPs are extended to assess higher-dimensional recurrence plots. Developed approach is applied to assess bone structure from 2D pQCT images of human proximal tibia.

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Recurrence Plot Analysis of Electrochemical Noise Data

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Electrochemical noise (ECN) data is commonly used to monitor and predict long-term corrosion of metals in various environments. In this work we use recurrence plots, a tool from the field of modern nonlinear data analysis, to study ECN time series of stainless steel AISI 316 samples immersed in mildly corrosive electrolytes. In particular, cross recurrence plots of current and potential time series are studied in order to identify various corrosion events taking place on the surface of the metallic samples. During general corrosion we found no clear relation between current and potential, which implies that the process has a high number of degrees of freedom or is random. However, during pit initiation, development, and decay the cross recurrence plots show a significant relation. This indicates that during pitting, trajectories of the current and potential remain close to each other in a low-dimensional space, and that this corrosion process is a deterministic nonlinear dynamic system with a small number of degrees of freedom.

Synchronization Analysis of Fixational Eye Movements by Means of Recurrence Plots

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The detection of phase synchronization in complex systems is often problematic, because the phase cannot be properly defined. We show how to exploit the recurrence properties of the systems to detect phase synchronization. This approach yields rather good results, even for very noisy time series. We exemplify the proposed method for the detection of synchronization in fixational eye movements.

Detection of Unstable Tori by Means of Recurrence Plots (Poster)

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In contrast to chaotic attractors composed by an infinite number of unstable periodic orbits, some attractors are composed also by unstable tori. This fact has important consequences for the dynamical behavior of the system and hence, it is important to detect whether there are unstable tori embedded in the attractor. We show how to detect unstable tori by means of RPs. This is an advantage with respect to the direct computation of the Lyapunov spectrum, because using RPs it is not necessary to know the equations of the underlying system.

On Recurrences (Introduction)

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In this introductory talk the important role of recurrences within the framework of the theory of dynamical systems will be discussed.

Dynamical Invariants and Surrogates from Recurrence Plots

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Recurrence Plots (RPs) have been used successfully to study the dynamics of measured time series. They visualise the dynamics and can be quantified by ad hoc measures, which allow gaining new insights into the systems under study. But RPs are also closely linked to fundamental concepts of nonlinear dynamics. We present results on how dynamical invariants can be obtained from RPs and show that "all relevant" dynamical information is contained in the recurrence matrix. We then use these results to construct alternative evolutions of the system (surrogates), which we use to perform an hypothesis test to assess the reliability of a synchronisation analysis.

Comparing Modern and Pleistocene ENSO-like Influences in NW Argentina Using Cross Recurrence Plot Analysis

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Climatic changes are of major importance in landslide generation in the Argentine Andes. Increased humidity as a potential influential factor was inferred from the temporal clustering of landslide deposits during a period of significantly wetter climate, 30,000 years ago. A change in seasonality was tested by comparing past (inferred from annual-layered lake deposits, 30,000 years old) and modern (present-day observations) precipitation changes. Quantitative analysis of cross recurrence plots has been developed to compare the influence of the El Niño/Southern Oscillation (ENSO) on present and past rainfall variations [1]. This analysis has revealed a stronger influence of NE trades in the location of landslide deposits in the intra-andean basin and valleys, what caused a higher contrast between summer and winter rainfall and an increasing of precipitation in La Niña years. This is believed to reduce thresholds for landslide generation in the arid to semiarid intra-andean basins and valleys.

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Anti-Deterministic Data That are More Unpredictable Than Noise

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We present a new type of deterministic dynamical behaviour that is less predictable than white noise. We call it anti-deterministic (AD) because time series corresponding to the dynamics of such systems do not generate deterministic lines in Recurrence Plots for small thresholds. We show that although the dynamics is chaotic in the sense of exponential divergence of nearby initial conditions and although some properties of AD data are similar to white noise, the AD dynamics is in fact less predictable than noise and hence is different from pseudo-random number generators.

Spatial Recurrence Plots in Snapshot Patterns of Coupled Map Lattices

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We propose an extension of the recurrence plot concept to perform quantitative a nalyzes of roughness and disorder of spatial patterns at a fixed time. We introd uce spatial recurrence plots (SRPs) as graphical representation of the pointwise correlation matrix, in terms of a two-dimensional spatial return plot. This tec hnique is applied to the study of complex patterns generated by coupled map latt ices (CML), which are characterized by measures of complexity based on SRPs. We show that the complexity measures we propose for SRPs provide a systematic way o f investigating the distribution of spatially coherent structures, such as synch ronization domains, in lattice profiles. This approach has potential for many mo re applications, e.g., in surface roughness analyses.

Recurrence Quantifications: Feature Extractions from Recurrence Plots

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In a brief paper entitled "Recurrence Plots of Dynamical Systems", Eckmann, Kamphorst and Ruelle (1987) used distance matrices of embedded dynamics to reveal hidden patterns in dynamical systems. Webber and Zbilut (1994) soon recognized the applicability of the technique to physiological systems which are notoriously nonlinear, nonstationary, and noisy. Instead of relying on subjective visual inspections of graphs, however, succinct rules were defined whereby quantitative features of recurrence plots could be extracted reliably - hence the name, recurrence quantification analysis (RQA).

Features extracted from recurrence plots are termed recurrence quantifications. Each of the seven quantifications is some primary derivative of distributed points within a sparse, two-dimensional recurrence matrix. Possible arrangements of points include: isolated points, diagonal lines, vertical lines, and horizontal lines. Secondary structures such as thickened lines, squares and rectangles arise when points and lines of different types abut with each other. The seven RQA variables include: 1) %recurrence (density of recurrent points); 2) %determinism (proportion of points in diagonal line segments); 3) maxline (length of the longest diagonal line); 4) entropy (Shannon information entropy of the distributed diagonal line lengths); 5) trend (homogeneity or heterogeneity of recurrent points); 6) %laminarity (proportion of points in vertical line structures); 7) trapping time (average length of vertical line structures). Each quantitative variable has a unique dynamical interpretation.

There are numerous examples demonstrating the utility of windowed recurrence quantifications in detecting state changes in nonlinear time series stemming from physiology and physics, to name but two fields. Correct implementation of the methodology is contingent upon the proper setting of several recurrence parameters including: 1) delay; 2) embedding dimension; 3) norm; 4) window size; 5) window overlap; 6) radius; 7) line definition. Recurrence quantifications show differential sensitivities to parameter selections, but most notably the inclusion radius. That is, if the radius is too small, the most common features in the plot will be isolated points. If the radius is too large, the features will meld together and saturate. In windowed recurrences, therefore, it is becoming apparent that %recurrence can be clamped at a target value (e.g. 2%) to set an even playing field for interpreting the remaining quantifications. These concepts will be explored in much greater depth using clarifying examples.

Recurrence Plots for Analysing Heart Rate Variability Before Life-Threatening Cardiac Arrhythmias

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The knowledge of transitions between regular, laminar or chaotic behaviour is essential to understand the underlying mechanisms behind complex systems. While several linear approaches are often insufficient to describe such processes, there are several nonlinear methods which however require rather long time observations. To overcome these difficulties, we propose measures of complexity based on vertical structures in recurrence plots and apply them to the logistic map as well as to heart rate variability data. For the logistic map these measures enable us not only to detect transitions between chaotic and periodic states, but also to identify laminar states, i.e. chaos-chaos transitions. The traditional recurrence quantification analysis fails to detect the latter transitions. Applying our new measures to the heart rate variability data, we are able to detect and quantify the laminar phases before a life-threatening cardiac arrhythmia thereby facilitating a prediction of such an event. The maximal vertical line length using an embedding dimension of 6 and a radius of 110 ms is 283.7 ± 190.4 before ventricular tachycardia vs. 179.5 ± 134.1 at a control time ($p < 0.01$). A comparison to the previous applied methods from symbolic dynamics and the finite-time growths rates is given. Our findings could be of importance for the therapy of malignant cardiac arrhythmias.

Shrimp Structure and Associated Dynamics in Parametrically Excited Oscillators

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We investigate the bifurcation structures in a 2-dimensional parameter space (PS) of a parametrically excited system with two degrees of freedom both analytically and numerically. By means of the Rényi entropy of second order K_2, which is estimated from recurrence plots, we uncover that regions of chaotic behavior are intermingled with many complex periodic windows, such as shrimp structures in the PS. A detailed numerical analysis shows that the stable solutions lose stability either via period doubling, or via intermittency when the parameters leave these shrimps in different directions, indicating different bifurcation properties of the boundaries. The shrimps of different sizes offer promising ways to control the dynamics of such a complex system.

Recurrence Quantification Analysis: Introduction and Historical Context

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The last decade has witnessed curious developments in the analysis of dynamical signals: the original hope that chaos theory would help elucidate complex systems has met with some uncertainties. Initially, it was hoped that chaotic invariants could capture subtle nonlinear aspects of dynamical systems. But as more investigators become aware of the mathematical requisites (and limitations) of chaotic measures such as Liapunov exponents and dimensions, they have recognized that new tools are needed. An important recognition in this respect is that many natural signals, in addition to being nonlinear, tend to be nonstationary, noisy and high dimensional. Certainly such a statement is not revolutionary, however, during a time when new, exciting concepts are emerging, it sometimes becomes easy to overlook basic facts, and to ignore fundamental assumptions.

In this context, a rather short, simple paper by Eckmann, Kamphorst and Ruelle was published. In evaluating a physical experiment, the authors embedded the time series in a higher dimensional space, and then plotted the recurrences in a distance matrix according to a rule defining an error tolerance. To their surprise patterns were viewed which were previously not apparent in the original series. What is remarkable about this method is that the algorithm requires no mathematical transformations or assumptions. Indeed, one of the purported uses for this method was to identify nonstationarities or changes of state.

Although the visual features of such plots are appealing, a drawback was their qualitative nature. As a result, we set out to see if some of these features could be meaningfully quantified. The results of these efforts, with emphasis on practical application as well as brief examples of their use as well as comparison with traditional methods such Fourier transforms will be presented.

Spatial Stochastic Resonance in Spider Silk as Detected by Recurrence Analysis (Poster)

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Amino acid repeats or motifs have engendered interest because of their significance for physical characteristics as well as folding properties of proteins. Spider dragline silk proteins are noteworthy for their long repetitive sections, and are assembled from a soluble to an insoluble state during the silk production process. Computational analysis compared with in vitro measurements suggest that the silks amplify their repetitive hydrophobic regions through a type of stochastic resonance generated by the addition of a non-repetitive sequence, thus allowing them to form insoluble threads out of a soluble feedstock.

Recurrence Plot Analysis of Climatic and Sunspot Time Series

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Our paper is devoted to practical application of recurrence plots analysis to natural time series. The work is based on cross-recurrence Matlab toolbox developed by Norbert Marwan. Analysis of historical instrumental records of climatic data and solar activity proxies was performed to find their complex relationships, long-term changes and synchronization. We also discussed a problem of the global change of "space climate" and unprecedented high warmth of the Earth's climate. Uniqueness of cross-recurrence relationships between solar and climate dynamics since 1930's was established. Temperature series for northern and southern hemispheres of the Earth are also considered with carrying out tracing the hemispheric synchrony and asynchrony. Similar analysis was made for the north-south asymmetry of the solar activity.

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