Inferring signatures of determinism in the LFF regime of semiconductor lasers with optical feedback

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- Andres Aragoneses
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Where are we?

UPC Campus Terrassa

Gaia research Building
Sequences of events generated by complex systems
   - Intervals between threshold crossings and barrier crossings,
   - Neurons: inter-spike intervals (ISIs),
   - Human communication: inter-event user times (SMS, emails, Twitters).
   - Earth and climate: earthquakes, extreme events (tornados, rainfalls), etc.

Interplay of
   - Different time scales, memory
   - Nonlinear, high dimensional & stochastic effects

The identification of patterns in the sequence of events can allow for
   - Model verification, parameter estimation
   - Classification of different types of dynamical behaviors
   - Improving predictability and forecasting
Introduction: semiconductor lasers with feedback as high-dimensional & stochastic dynamical systems

Method of time-series analysis and experimental setup

Results. Experimental and model observations: inferring signatures of determinism + response to periodic forcing

Conclusions and take home message
Semiconductor laser with optical feedback: optical spikes

With optical feedback the laser *intensity* displays LFF dropouts similar to neuronal *spikes*.

- Complex interplay of:
  - Feedback delay time
  - Noise
  - Nonlinearity

⇒ Stochastic and high-dimensional system
To develop a method of time-series analysis that allows inferring signatures of determinism in the sequence of optical spikes;

To extract new information;

To compare model predictions with observations;

To explore potential for building optical neurons.
Governing equations


\[ |E|^2 \sim \text{photon number (output intensity)} \]

\[ N \sim \text{number of carriers (electron-holes)} \]

\[ \frac{dE}{dt} = \frac{1}{2\tau_p} (1 + i\alpha)(G - 1)E + \eta E(t - \tau)e^{-i\omega_0 \tau} + \sqrt{\beta_{sp}} \xi \]

\[ \frac{dN}{dt} = \frac{1}{\tau_N} \left( \mu + N - G|E|^2 \right) \]

Gain: \[ G = \frac{N}{1 + \varepsilon|E|^2} \]

feedback
noise

\[ \eta = \text{feedback strength} \]
\[ \tau = \text{feedback delay time} \]
\[ \mu = \text{pump current} \]

(control parameter)

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- The dropouts are a **transient** dynamics.

- Burst of dropouts are triggered by **noise**.

- In experimental sequences of dropouts: which ones are **deterministic** and which ones are **stochastic**?

- Main problem: we can measure only one relevant variable (the laser intensity)
- Also a problem: the measure system (photodiode, oscilloscope) has a finite *bandwidth* that gives a limited temporal resolution.

**Approach:** event-level description. We study the sequence of *inter-dropout-intervals*: $\Delta T_i = t_{i+1} - t_i$
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Symbolic ordinal analysis

- It has been used to analyze data generated from complex systems
  - Financial, economical
  - Biological, life sciences
  - Geosciences, climate
  - Physics, chemistry, etc

- It has been shown to be able to:
  - Distinguish stochasticity and determinism
  - Classify different types of dynamical behaviors (pathological, healthy)
  - Quantify complexity
  - Identify coupling and directionality.

“words” of D letters can be formed by considering the order relation between sets of D values \{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}.

For D=3 there are 6 possible orders

- Advantage: the transformation keeps information about correlations in the time-series & does not need a threshold
- Drawback: it does not keep information about the values, the set (5,1,100) also gives word “102”.

Example: the set (5, 1, 7) gives “102” because 1 < 5 < 7
Number of possible ordinal patterns: \( D! \)

- How to select \( D \)? Optimal \( D \) depends on:
  - The length of the time series.
  - The time scale of correlations.
- For optical spikes: \( D=2 \) (\( D=3 \)) unveil correlations of 3 (4) spikes

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Conclusions and take home message
Laser Diode 50/50 Beamsplitter External reflector

Detector to Oscilloscope

Temperature and pump current combi controller

External cavity - 45 cm

Hitachi Laser Diode (HL6724MG)

\[ \lambda \approx 674.2 \text{ nm} \]

5mW

\(~ 7\% \text{ threshold reduction}~

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Experimental inter-dropout-intervals (IDIs in lasers – ISIs neurons)

Laser output
(1 GHz oscilloscope)

$<\Delta T> = 100-200 \text{ ns}$
$\tau \sim 5 \text{ ns}$

# of IDIs recorded
45,000 - 220000

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IDI distributions

Is there any **information** in the ‘spike’ sequence?

Analogous to deciphering a foreign text.

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• Conclusions and take home message
Correlations between 3 consecutive spikes: probabilities of 01 & 10

Consistent with stochastic at low pump current, but signatures of determinism at high pump current.

D=2: 3-spike correlations?

Null hypothesis: fully random sequence of spikes \( \Rightarrow P(01) = P(10) \)

At low pump current: are the spikes fully random? New experiment

Also in another data set recorded at a different temperature (T=20 C)
Are the deviations from the null hypothesis significant?

Recorded data

Surrogated data
Which dropouts are noise-induced and which ones are deterministic?

We use a **threshold** to classify the inter-dropout-intervals as **short** and **long** intervals.
At high currents: significant differences
  — LIs consistent with random events
  — SIs more deterministic.

But at low pump currents, the inter-spike-intervals can not be classified in two types with significant differences.

Constructing the words with 3 consecutive SIs or LIs

Similar results in the other dataset (T=20 C)

At high pump currents an adequate threshold allows classifying the events in two distinct categories
Investigadores de la UPC de Terrassa crean un nuevo método para identificar el orden dentro de sistemas caóticos complejos

La técnica se podría utilizar para estudiar el comportamiento de las redes sociales, los terremotos o de la actividad neuronal.

Miércoles, 26 de junio del 2013 - 12:00

J. S. / Terrassa

En la película ‘Contact’ (1997), protagonizada por Jodie Foster, el equipo de científicos que averiguaron el origen y el significado de unas señales acústicas extraterrestres acaban por descubrir que detrás del ruido y de la frecuencia temporal de los sonidos escondían camuflados, entre un supuesto caos, imágenes de la Historia Contemporánea y los planos de una misteriosa esfera.

Recientemente, y en la ciencia real, un equipo de investigadores del grupo de investigación Dinámica No Lineal, Óptica no Lineal y Láseres (DONLL) de la Universitat Politècnica de Catalunya-BarcelonaTech (UPC) en el Campus de Terrassa y de la Universidad de Aberdeen han conseguido con una nueva metodología mucho más sencilla que las que se utilizaban hasta ahora, separar el orden del caos. El trabajo se ha publicado en la prestigiosa revista ‘Scientific Reports’.

Los investigadores han desarrollado un método muy accesible, tanto desde el punto de vista conceptual como de aplicación, por lo que han venido a dosificar el grupo de inestabilidad que se manifiesta con una distribución aleatoria y de otro, el grupo de inestabilidades con una fase de señales y una estructura analítica.

La UPC crea un sistema para distinguir el orden del caos

La técnica podría ser útil en medicina y redes sociales

Redacción

Un equipo de investigadores del campus de la Universitat Politècnica de Catalunya (UPC), junto con científicos de la Universidad de Aberdeen de Escocia, han desarrollado un nuevo método, basados en señales, para distinguir comportamientos similares en sistemas caóticos. El trabajo se ha publicado en la prestigiosa revista ‘Scientific Reports’.

EJEMPLOS PRÁCTICOS

Sobre el tema se ha explicado que ‘un mismo patrón de orden y caos en un sistema complejo’ puede ser una herramienta muy útil en campos como la medicina y las redes sociales.”

Cristina Masoller, Carmen Torrent y Andrea Aragonés, parte del equipo de la UPC de Terrassa que ha creado un nuevo método para identificar el orden dentro de sistemas caóticos complejos UPC TERRASSA

FP_BI_noticia_canal_terrasaa.wmv
Ordinal analysis unveils new information

There is a hierarchical and clustered organization of the probabilities of the words
In another experiment: also the same hierarchy and the same 2 clusters

75,000 – 880,000 dropouts
(different laser, new oscilloscope)
Sensitivity to the threshold that defines the event times?

The hierarchy and the clusters are robust to the threshold chosen to define the spike times.
Can we find a minimal model that displays these features?

Logistic map

Tent map

Map parameter

P-1/6

Map parameter
A modified circle map: minimal phenomenological model

\[ \varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi} \left[ \sin(2\pi \varphi_i) + \alpha \sin(4\pi \varphi_i) \right] \]

\[ X_i = \varphi_{i+1} - \varphi_i \]

\[ \rho = 0.23 \]
\[ K = 0.04 \]

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Periodic modulation of the laser current

Laser intensity:

- Increasing the modulation amplitude

Time (ns)

λ = 660 nm

λ = 1550 nm

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Experiments @ 660 nm

Experiments @ 660 nm (68,000 - 200,000 dropouts)

Minimal circle-map model

\[ \phi_{i+1} = \phi_i + \rho + \frac{K}{2\pi} \left[ \sin(2\pi \phi_i) + \alpha \sin(4\pi \phi_i) \right] + D\zeta \]

Similar observations @ 1550 nm

\[ \rho = -0.23 \]
\[ \alpha = 0.2 \]
\[ D = 0.02 \]
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Conclusions and take home message
We proposed a novel method to infer signatures of determinism in sequences of events in dynamical complex systems. Adequate for high-dimensional & stochastic systems displaying noise or deterministically induced events.

We found new symbolic states with an hierarchical and clustered organization of the probabilities of the patterns.

We identified a minimal phenomenological model.

LK model is in good agreement with observations (not shown)

Potential breakthrough: optical neurons for neuro-inspired information processing.
- Ordinal analysis is a powerful technique for the event-level description of complex systems
  - useful for data understanding and uncovering patterns in the sequence of events,
  - useful for improving system modeling, model comparison and parameter estimation,
  - useful for classifying different types of behaviors,
  - potential for improving event predictability and forecasting.
Andres Aragoneses

Thanks to Carme Torrent

You for your attention!

Papers @ www.fisica.edu.uy/~cris

– J. Zamora-Munt et al, PRA 2010
– N. Rubido et al, PRE 2011
– A. Aragoneses et al,
  http://www.nature.com/srep/2013/130507/srep01778/full/srep01778.html