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Innovation and Complexity from Physics
to Medicine and Pharmaceuticals

BOOK of ABSTRACTS

Editors:
Stavros G. Stavrinos
Mehmet Özer

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PART I
INVITED TALKS

From Complex Systems and Nonlinear Dynamics to Neuromorphic Systems and Physical AI

Klaus Mainzer

*President of the European Academy of Sciences and Arts, Salzburg, Austria
TUM Senior Excellence Faculty, Technische Universität München, Munich, Germany
Carl Friedrich von Weizsäcker-Center, Eberhard-Karls-Universität Tübingen, Germany*

Abstract

According to several prominent authors, a main part of 21st century science will be on complex systems and their nonlinear dynamics. Recently, these results of complexity research have become important for complex pattern recognition of artificial neural networks (ANN). But ANN-systems are only simulated on digital computers with severe problems of energy consumption - in contrast to the highly energetically efficient biological brains. Therefore, neuromorphic systems with more brain-orientated computing should be considered also for hardware realization.

Such as brains in living organisms, neuromorphic systems should be integrated into physical AI systems. Living organisms do not only learn from datasets, but from physical contact with an environment through resistance, balance, and feedback.

But humans do not only learn through physical interaction and data processing with statistical correlations, but by causal learning from assumed causal knowledge of physical laws. Therefore, classical neural networks have been recently extended as physics-informed neural networks even for applications in socio-technical infrastructures. Neuromorphic systems with Physical AI and physics-informed neural networks promise more human-like, more efficient, and resource-saving systems which overcome traditional limitations by learning from nature.

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PLENARY TALK

Complexity and chaotic dynamics of cardiac arrhythmias

Ulrich Parlitz

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Institute for Complex Dynamical Systems, Georg-August-Universität Göttingen, Göttingen, Germany*

Abstract

The heart muscle is a complex network of electrically and mechanically excitable cardiomyocytes, whose synchronized contraction ensures the vital pumping function. However, the coherent contraction can be (significantly) impaired by the occurrence of stable or chaotic spiral waves, leading to (life-threatening) arrhythmias including atrial or ventricular fibrillation. In our contribution, we discuss properties of this type of (often transient) spatiotemporal chaos and novel approaches for low-energy defibrillation that utilise the response to certain external disturbances and feedback.

Memristive arrays at the edge of chaos: Recent results

Ronald Tetzlaff

Institute of Circuits and Systems, TU Dresden, Germany

Abstract

Following the theory derived by L. O. Chua [1], it becomes clear that locally passive systems are unable to support the development of complex spatio-temporal patterns [1]. It follows that the occurrence of emergent phenomena in a nonlinear dynamic system requires that some of its fundamental components are capable of amplifying a small signal and thus exhibit the characteristic of local activity. In particular, the root of complexity lies in a certain sub-domain of the local activity regime known as the “edge of chaos.”

Contrary to expectations, passive coupling of two cells sitting on a stable operating point can lead to destabilization of the homogeneous solution, with the basic units of such a structure asymptotically approaching either two different operating points or a pair of different oscillatory solutions.

This phenomenon was originally demonstrated by Smale [2] and recently explained by edge of chaos theory. This phenomenon is of particular technical significance for the development of appropriate computer systems for implementing AI strategies. Current work on analog computing arrays, in particular with Cellular Nonlinear Networks (CellINN), which have already demonstrated high performance in CMOS technology for image processing applications, can be used to solve multidimensional signal processing tasks with maximum efficiency by incorporating memristors and positioning them at the edge of chaos.

This talk presents recent research results on the development of memristor array technologies to demonstrate the potential of this theory to explain emerging complex phenomena and provide strategies for future high-performance multidimensional signal processing applications at the edge of chaos.

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The Pathway to Knowledge: Learning versus Modeling

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Abstract

After Thales and Pythagoras, prediction has been achieved through finding the solutions of mathematical models (dynamical systems), which are discovered by observing natural phenomena. This tradition is taught in Physics and is extended as a scientific method to the various manifestations of human experience.

The development of Differential and Integral Calculus showed, at the end of the 19th century, that the solutions of dynamical models can also be found by solving equivalent minimum problems — the principles of Hero, Fermat, Maupertuis, Hamilton, and Lagrange. This idea was extended to Partial Differential Equations, by Weierstrass and Carathéodory, which describe fluids and electrodynamics; to Quantum Theory, by Dirac and Feynman; and also to economics, by von Neumann, Kantorovich, and Dantzig.

The Calculus of Variations and Optimization today constitute autonomous fields of knowledge. The advantage of the Principle of Least Action, or more generally of minimum principles, is that solutions can be found without knowledge of the dynamical model. This observation has been exploited in Machine Learning, which constitutes the basis of Artificial Intelligence.

The relevant methods minimize suitable functions (prediction error relative to observation, loss, risk, cost) on the basis of corresponding representation theorems, such as those of Weierstrass and Kolmogorov.

Hadamard pointed out in 1902 that prediction is impossible in practice if the mathematical problem is not well posed. That is, three conditions must be satisfied: existence, uniqueness, and stability of the solution. Poincaré had already revealed Chaos as an example of a problem that is not well posed, due to sensitivity to initial conditions.

It was later proved, by Hopf and Wold, that every dynamical system, as well as every time series, can be decomposed into a predictable and a non-predictable part. Kolmogorov showed that Entropy is preserved in the predictable part, whereas Entropy production is the signature of the non-predictable part.

Chaos, which appears in mathematical models as well as in the time series encountered in practice, is a typical example of non-predictability. It is found that machine learning, specifically Reservoir Computing Networks, does not improve the predictability of chaotic time series compared to computations based on dynamical models. This is not surprising, since optimization problems are likewise not well posed.

Machine learning is however, the only available tool for data analysis when we do not know the mathematical model underlying the observations. If entropy is produced by some part of the observations, then predictions through machine learning are less reliable compared to predictions based on dynamical computations. The problem is particularly acute in data with high volatility.

Keywords: predictability, chaos, machine learning, minimum principles, knowledge

One NaMLab Memristor on Edge of Chaos Enables Small Signal Amplification in an Otherwise-Dumb Analogue Electrical Cell

Alon Ascoli

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Abstract

In a recent paper [6], Brown et al. experimentally demonstrated small-signal gain at the output of a simple metallic line, when the physical medium it was preliminarily integrated upon was biased on the Edge of Chaos (EOC), the stable region of the Local Activity domain [7], where a dynamical system hides a high degree of excitability behind a silent steady state, which is the *Conditio Sine Qua Non* for the emergence of complex spatio-temporal phenomena ([1], [2], [8]) enabling the execution of otherwise-impossible data processing tasks [9], across its physical medium, under tiny perturbations of its nominal operating conditions. Exploiting this scientific breakthrough, it is now possible to transmit a small signal through a conductor without the need to introduce amplification units at regular intervals across its physical structure to compensate for the propagation losses.

In this presentation, we show how EOC in a NbOx-based threshold switch from NaMLab [4] is crucially necessary for the extraction of small-signal voltage gain across at least one of the two output ports of a simple analogue electrical circuit, composed of the series combination between a linear resistor, a voltage source generating an infinitesimal sine wave with some appropriate offset, and a volatile NbOx threshold switch [3]. Recurring to linearization techniques and to basic concepts from Control Theory, we identified the necessary and sufficient conditions for small-signal voltage amplification across the three-element analogue electrical cell. Interestingly, these conditions may be tuned by massaging the circuit parameters responsible for polarizing the threshold switch on a negative differential resistance (NDR) operating point.

Moreover, our theoretical analysis [5], awaiting now an experimental validation, reveals how, despite being an essential requisite, the provision of local energy of the NaMLab volatile memristor on EOC to the one voltage source-one resistor series one-port it is coupled to, is insufficient to induce small-signal voltage gain in the proposed second-order cell across a specific input frequency band. All in all, our in-depth study sheds light into the mechanisms underlying the small-signal voltage amplification capabilities of a simple circuit leveraging stable NDR effects in a physical memristor realization.

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Anticipated Synchronization in Delay-Coupled Nonlinear Systems

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Abstract

Anticipated synchronization (AS) is a counterintuitive dynamical phenomenon in which a driven system reproduces the future state of a driver system to which it is unidirectionally coupled, without altering the driver's intrinsic dynamics. Since its original theoretical formulation by H. Voss, AS has attracted much attention due to its conceptual novelty and its implications for prediction, control, and information processing in nonlinear systems. In this lecture, I will review the development of the field, from its foundational theoretical proposals to recent advances in complex, chaotic, excitable, and biological systems.

I will begin by presenting the basic mechanism underlying anticipated synchronization in driver-driven configurations with delayed self-feedback, emphasizing analytical results obtained for linear systems. Particular attention will be devoted to recent extensions of the classical single-delay framework to the more realistic case of distributed-delay coupling. In many physical and biological systems, interactions occur through multiple pathways or with uncertain transmission times, leading naturally to delay distributions rather than a single fixed delay. I will show how the effective anticipation time and amplification properties of the driven system are determined by the characteristics of the delay distribution, and how distributed delay can enlarge the region of parameter space supporting stable anticipation.

I will then address chaotic and non-autonomous dynamics, including extended systems, where exact anticipation is replaced by robust forms of approximate synchronization. I will discuss how anticipation manifests itself in chaotic trajectories, how it can be quantified, and how distributed delay modifies stability and amplification properties in these strongly nonlinear regimes. An especially important outcome of this line of research is the development of the predict- prevent control strategy: by exploiting the anticipatory signal generated in the driven system, it becomes possible to suppress unwanted excitation events in the driver before they fully develop. This predictive control mechanism highlights the potential functional relevance of anticipated synchronization.

An important focus of the lecture will be on excitable and neural systems. Work carried out at our institute, particularly by C. Mirasso and collaborators, has demonstrated that anticipated synchronization can emerge in biologically plausible neuronal circuits, including inhibitory feedback motifs and coupled excitable models. In these systems, delayed inhibitory loops can generate systematic spike anticipation and predictive phase relationships. By combining theoretical analysis, numerical investigation, and interdisciplinary applications, the field continues to reveal how delayed interactions can generate and exploit predictive behavior in complex systems.

Artificial intelligence and complex classical and quantum systems

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Abstract

Pioneering research contributions in Artificial Intelligence (AI) received two Noble prizes in Physics and two in Chemistry in 2024. John Hopfield and Geoffrey Hinton got the Physics prize while Demis Hassabis and John Jumper got the Chemistry prize all for work related to the development and applications in AI. In 2021 Giorgio Parisi received the Physics Nobel prize for work in Complex dynamical and statistical systems. Most recent developments in AI are founded on networks of artificial neurons that are themselves very complex and involved. On the other hand, complexity is typically thought to involve chaos, solitons, fractals and self-organization [1,2,3]. Linking complex systems with AI is intriguing since it might provide clues on how to better deal with nonlinear systems using machine learning and similar techniques. Furthermore, complex systems work may enable the deeper, possibly statistical, understanding of complicated AI networks. In this talk I will present ideas and results on how to apply machine learning in complex dynamical systems and learn something new about these systems [4]. One basic question is whether we can actually teach the computer to learn solutions of physical problems. We will present a number of results showing that the answer is generally affirmative, even though precise analytical foundations are lacking. We also focus on the use of quantum computation as a tool for perhaps more efficient handling of machine learning analysis. In this context we will address medical applications as well as more fundamental questions as the detection of “quantumness” in biological and other data.

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PART II
EXTENDED ABSTRACTS

Compact Finite Differences Method and Caputo Fractional Derivative Definition for a One-Dimensional Space Fractional Diffusion Equation

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Extended abstract

Introduction. This study presents a numerical treatment for a one-dimensional non-homogeneous space fractional diffusion equation with initial and boundary conditions. The main objective is to combine a compact finite difference framework with the Caputo fractional derivative definition in order to obtain a stable and accurate approximation for the fractional diffusion operator. The paper is motivated by the well-known limitation of classical finite difference schemes: increasing the formal order of accuracy usually enlarges the stencil, complicates the treatment near boundaries, and broadens the bandwidth of the algebraic system. Compact schemes are preferred because they preserve high-order accuracy while keeping the stencil narrow and the resulting matrices computationally manageable [3][5].

Method. The spatial domain is discretized on a uniform mesh, while time is approximated with a finite difference step. For the first and second spatial derivatives, the method employs implicit compact schemes with high-order accuracy, leading to matrix formulations for the derivative vectors. The corresponding coefficient matrices are treated through LU decomposition so that the derivative terms can be written in operator form and inserted into the final discretization. The fractional component is handled through the Caputo definition, where the derivative of order α is represented by an integral involving the second derivative of the unknown function. After repeated integration by parts and Taylor expansion, the fractional term is reduced to a form involving the function and its first two derivatives, which makes it compatible with the compact finite difference framework. This produces a hybrid semi-discrete model in which the time derivative, the compact derivative operators, and the source term are assembled into a solvable linear system at each time level [5][9][13].

Results. The method is illustrated on a test problem posed on $0 \leq x \leq 1$ with initial condition $u(x,0)=x^3$, a prescribed diffusion coefficient, and a non-homogeneous source term. For validation, the numerical solution is compared against the exact solution available in the integer-order case $u(x,t)=e^{-t}x^3$. Computed maximum absolute errors are reported for different mesh sizes and time steps, showing that the approach reproduces the reference solution with satisfactory accuracy. The paper also includes a dispersion analysis in continuous and discrete form. By comparing the two dispersion relations, it is shown that the curves intersect at multiple points, which supports the consistency of the discrete model and indicates convergence as the mesh is refined. In practical terms, the results demonstrate that the compact finite difference approximation coupled with the Caputo derivative definition is an effective numerical technique for one-dimensional space fractional diffusion equations.

Conclusion. The contribution of the paper lies in showing that high-order compact approximations can be integrated successfully with a Caputo-based formulation of the space fractional derivative. The resulting method remains relatively economical in stencil width while preserving good approximation quality, including near the boundaries. The study therefore offers a useful alternative for the numerical treatment of fractional diffusion models where standard explicit discretizations may become inefficient or less accurate.

Keywords: fractional diffusion equation; Caputo fractional derivative; compact finite differences; high-order discretization; dispersion analysis.

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Numerical investigation of effective stability and chaos in the J_2 -Solar radiation pressure problem

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Extended abstract

The coupled solar radiation pressure (SRP) and oblateness (J_2) problem has been well-investigated in the literature, with work done, for example, in [1, 2, 3] to develop resonant models that describe the corresponding long-term evolution. Using the model derived in [3], we numerically investigate the coupled J_2 and SRP problem aiming to supplement the semi-analytical results obtained in [3]. Another objective of our study is to provide practical insights for end-of-life disposal strategies that could be useful to engineers working on this problem. To achieve this goal, we perform an analysis of the role of chaos in specific regions of the system's phase space.

The model we consider is a perturbed Hamiltonian system of the two-body problem, derived by considering perturbations due to the Earth's oblateness (J_2) and the SRP contribution. Starting from this perturbed system expressed in terms of the satellite's orbital elements ($a, e, i, \omega, \Omega, M$) (semi-major axis, eccentricity, inclination, argument of perigee, longitude of the ascending node, and mean anomaly respectively), we perform an average over the mean anomaly M , such that the Hamiltonian is given by:

$$\bar{\mathcal{H}} = \frac{\mu r_E^2 J_2 (1 - 3 \cos^2 i)}{4a^3 (1 - e^2)^{3/2}} - \frac{3a e c_R P}{2} \frac{A}{m} \sum_{j=1}^6 \mathcal{T}_j \cos \psi_j. \quad (1)$$

In Eq. (1), r_E is the Earth's radius, J_2 its oblateness parameter, c_R the satellite's reflectivity coefficient and A/m its area-to-mass ratio, while P is the SRP constant at 1 astronomical unit. We also set $\mu = \mathcal{G}m_E$ with $\mathcal{G}$ being the gravitational constant and m_E the mass of Earth. The quantities $\mathcal{T}_j$, $j = 1, 2, \dots, 6$ are the coefficients of the six harmonics given in Table 1. We also set the obliquity of the ecliptic to $\varepsilon = 23.4^\circ$ and consider the ecliptic longitude of the Sun to be $\lambda_\odot = \lambda_{\odot,0} + n_S t$ where $\lambda_{\odot,0}$ is defined by astronomical ephemerides and n_S is the Sun's mean motion. We then express Hamiltonian (1) in terms of the canonical Delaunay variables (L, G, H, l, g, h) given by $L = \sqrt{\mu a}$, $l = M$, $G = L\sqrt{1 - e^2}$, $g = \omega$, $H = G \cos i$, $h = \Omega$, and finally transform the obtained non-autonomous Hamiltonian to an autonomous one by extending the system's phase space by introducing a dummy action J to account for the time-dependence in $\lambda_\odot = \lambda_{\odot,0} + n_S t$. In this way, the final form of the three degrees of freedom Hamiltonian is:

$$\bar{\mathcal{H}} = \frac{(r_E^2 J_2 \mu^4)(G^2 - 3H^2)}{4G^5 L^3} + n_S J - \frac{3(c_R P \frac{A}{m}) L^2}{2\mu} \sqrt{1 - \frac{G^2}{L^2}} \sum_{j=1}^6 \mathcal{T}_j \cos \psi_j. \quad (2)$$

We use the Smaller Alignment Index (SALI) to distinguish between regular and chaotic motion. Following [4, 5], the SALI is computed by simultaneously integrating the equations of motion of an orbit and the corresponding variational equations for two initially linearly independent deviation vectors, $\mathbf{w}_1(0)$ and $\mathbf{w}_2(0)$ from it. Then, the SALI is defined as

$$\text{SALI}(t) = \min\{\|\widehat{\mathbf{w}}_1(t) \pm \widehat{\mathbf{w}}_2(t)\|\} \quad (3)$$

where $\|\cdot\|$ denotes the usual Euclidean norm and $\widehat{\mathbf{w}}_i(t) = \mathbf{w}_i(t)/\|\mathbf{w}_i(t)\|$, $i = 1, 2$ are the corresponding unit vectors. For chaotic orbits, both deviation vectors tend to align along the direction associated with the maximum Lyapunov exponent. As a result, the SALI tends to zero, following an exponential decay governed by the two largest Lyapunov exponents, $\lambda_1 \geq \lambda_2$, namely $\text{SALI}(t) \propto e^{-(\lambda_1 - \lambda_2)t}$. In contrast, for regular motion in a Hamiltonian system with $N \geq 2$ degrees of freedom, the deviation vectors will eventually fall on the N -dimensional tangent space of the invariant torus. As there is no mechanism enforcing their alignment, the SALI remains approximately constant, exhibiting only small fluctuations around a positive value.

j	$\mathcal{T}_j$	$\cos \psi_j$
1	$\frac{1}{4}(\cos \varepsilon + 1)(\cos i + 1)$	$\cos(\omega + \Omega - \lambda_\odot)$
2	$-\frac{1}{4}(\cos \varepsilon + 1)(\cos i - 1)$	$\cos(-\omega + \Omega - \lambda_\odot)$
3	$\frac{1}{2} \sin i \sin \varepsilon$	$\cos(\omega - \lambda_\odot)$
4	$-\frac{1}{2} \sin i \sin \varepsilon$	$\cos(\omega + \lambda_\odot)$
5	$-\frac{1}{4}(\cos \varepsilon - 1)(\cos i + 1)$	$\cos(\omega + \Omega + \lambda_\odot)$
6	$\frac{1}{4}(\cos \varepsilon - 1)(\cos i - 1)$	$\cos(-\omega + \Omega + \lambda_\odot)$

Table 1: The six harmonics describing the semi-secular evolution of Hamiltonian (1).

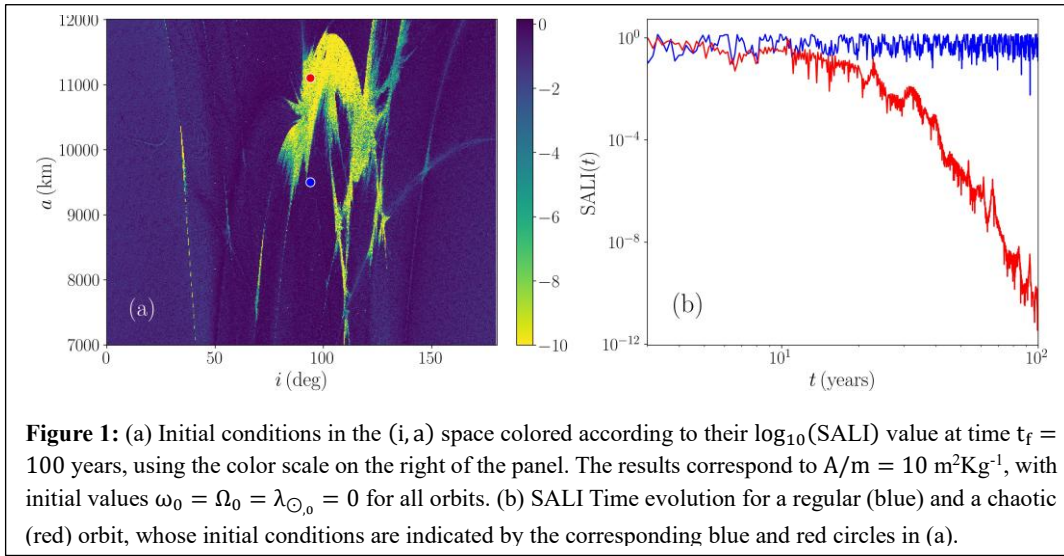


Figure 1: (a) Initial conditions in the (i, a) space colored according to their $\log_{10}(\text{SALI})$ value at time $t_f = 100$ years, using the color scale on the right of the panel. The results correspond to $A/m = 10 \text{ m}^2\text{Kg}^{-1}$, with initial values $\omega_0 = \Omega_0 = \lambda_{\odot,0} = 0$ for all orbits. (b) SALI Time evolution for a regular (blue) and a chaotic (red) orbit, whose initial conditions are indicated by the corresponding blue and red circles in (a).

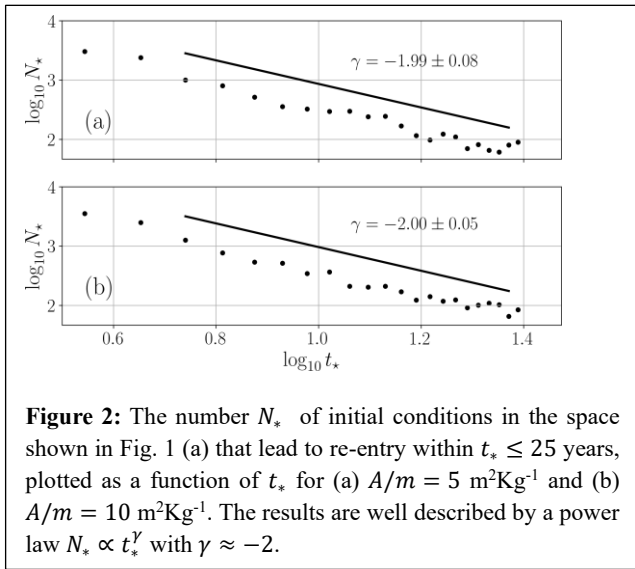


Figure 2: The number N_* of initial conditions in the space shown in Fig. 1 (a) that lead to re-entry within $t_* \leq 25$ years, plotted as a function of t_* for (a) $A/m = 5 \text{ m}^2\text{Kg}^{-1}$ and (b) $A/m = 10 \text{ m}^2\text{Kg}^{-1}$. The results are well described by a power law $N_* \propto t_*^\gamma$ with $\gamma \approx -2$.

statistical properties of re-entry times. We find that for entry within $t_* \leq 25$ years, follows a power law decay, i.e., $N_* \propto t_*^\gamma$, with $\gamma \approx -2$, as illustrated in Fig. 2.

To reveal the chaotic or regular nature of orbits that re-enter the Earth's atmosphere at time t_* , we evaluate, for each trajectory, the value of the SALI at time t_* (if $t_* \leq 25$ years). Remarkably, as observed in Fig. 3, within this operationally constrained timescale, all such orbits exhibit regular dynamical behavior up to their re-entry. This observation highlights that, despite the long-term presence of chaotic regions in phase space (see Fig. 1(a)), the subset of trajectories complying with the 25-year de-orbiting guideline evolves effectively regularly over the time interval of practical interest.

values (blue regions). In Fig. 1(b), we plot the time evolution of the SALI for a representative chaotic (regular) orbit, whose initial condition $i = 94^\circ$, $a = 11\,100 \text{ km}$ ($i = 94^\circ$, $a = 9\,500 \text{ km}$) is indicated by a red (blue) circle in Fig. 1 (a). We observe the expected exponential decay (practical constancy) of the index for chaotic (regular) motion.

The orbital lifetime of a satellite is defined as the re-entry time t_* , which corresponds to the instant at which the orbit reaches a critical eccentricity threshold $e_* = 1 - (r_E + \delta)/a_0$, with $\delta = 120 \text{ km}$ and a_0 being the orbit's initial semi-major axis. This condition serves as a proxy for atmospheric re-entry. Our analysis is deliberately restricted to a finite time horizon of 25 years, in accordance with internationally adopted space debris mitigation guidelines, which recommend that satellites be de-orbited within 25 years of the end of their operational lifetime. This constraint defines the natural temporal framework within which the dynamical behavior of orbits is assessed. Within this 25-year window, we first examine the large A/m ratios, the number N_* of initial conditions leading to re-

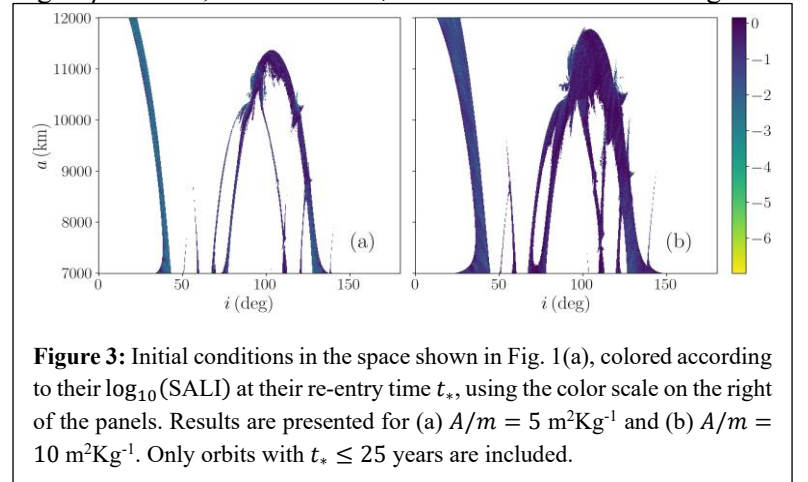


Figure 3: Initial conditions in the space shown in Fig. 1(a), colored according to their $\log_{10}(\text{SALI})$ at their re-entry time t_* , using the color scale on the right of the panels. Results are presented for (a) $A/m = 5 \text{ m}^2\text{Kg}^{-1}$ and (b) $A/m = 10 \text{ m}^2\text{Kg}^{-1}$. Only orbits with $t_* \leq 25$ years are included.

Keywords: Solar radiation pressure; Low Earth orbit; Chaos; Smaller Alignment Index; Hamiltonian systems;

Acknowledgments

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Imaging through Scattering Media using Temporally Coherent and Spatially Incoherent Special Optical Beams

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Extended abstract

Imaging through scattering media (ITSM) remains a challenge in biomedical imaging and remote sensing systems [1]. Due to multiple scattering within such media, which randomizes the phase and amplitude of incident light, there is a degradation of image contrast, spatial resolution, and overall fidelity. Overcoming these limitations requires both optical beam engineering and computational reconstruction methods to compensate for the scattering-induced distortions [2]. In this study, we present an experimental investigation of image retrieval through a thin scatterer using a broad class of special optical beams (SOBs) under temporally coherent and spatially incoherent (TCSI) illumination [3].

A computational imaging framework termed *Imaging through scattering media using temporally coherent and spatially incoherent special optical beams* (ITSM-TCSI-SOB) was proposed and experimentally demonstrated. The proposed approach employs engineered SOBs under TCSI illumination to encode object information through a thin scatterer, as illustrated in Figure 1. The recorded object intensity patterns are processed with a pre-recorded point spread function library under identical conditions using a deconvolution-based computational reconstruction algorithm called the Lucy-Richardson-Rosen algorithm (LRRA) to retrieve the object information [4].

In this study, a set of SOBs, such as Bessel beam, higher-order Bessel beam, Airy beam, self-rotating beam, and vortex beam, was employed. Experiments were conducted using thin scatterers with increasing scattering strengths to analyze their imaging performance under both weak and strong scattering conditions. The object information was modulated by each optical beam and transmitted through these scatterers to evaluate the extent to which spatial object information could be retrieved under different scattering strengths. In the experiment, the corresponding point spread function and object intensity patterns were processed using LRRA, which enables recovery of the object image.

This experimental study, along with quantitative evaluation, provides a detailed analysis of SOBs under TCSI illumination in the presence of a thin scatterer. While scattering imposes fundamental constraints on object image reconstruction accuracy, the results confirm that the engineered SOBs enable effective object image recovery. The proposed ITSM-TCSI-SOB method, therefore, represents a promising approach for imaging through a thin scatterer and offers potential pathways toward advanced optical imaging systems for biomedical imaging and remote sensing applications.

Keywords: computational imaging; scattering media; special optical beams; deconvolution.

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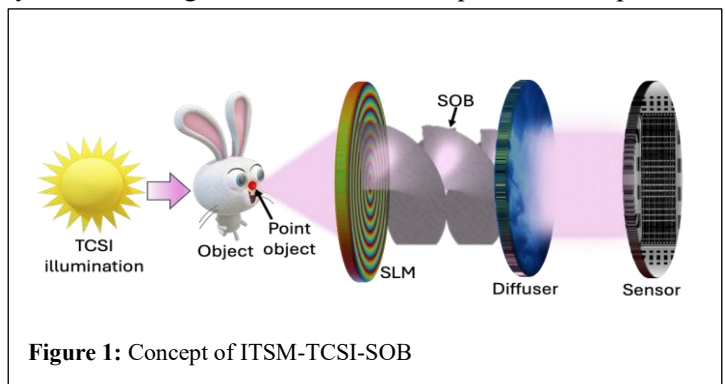


Figure 1: Concept of ITSM-TCSI-SOB

A Multi-Layered Adaptive Security Architecture for Generative AI-Driven Web Systems under Emergent Threat Dynamics

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Extended abstract

The integration of generative artificial intelligence (AI) into web-based systems introduces not only new capabilities but also highly complex and unpredictable system behaviors[1][2]. Unlike traditional software architectures, these systems exhibit dynamic, context-sensitive, and often non-linear interactions, leading to the emergence of novel security risks. Threats such as prompt injection, data leakage, manipulation of model outputs, and API-based exploits evolve within this complex environment, forming interconnected and cascading risk structures[3]. This study approaches generative AI-enabled web applications as complex adaptive systems and aims to analyze emerging security risks through a systems-oriented perspective. To this end, a prototype web application simulating organizational workflows was developed, and controlled attack scenarios were conducted to observe system behavior under adversarial conditions. The findings indicate that security vulnerabilities cannot be adequately understood as isolated issues, but rather as emergent phenomena resulting from system-level interactions. Accordingly, risks were evaluated not only in terms of probability, impact, and exploitability, but also with respect to their propagation, interaction effects, and the role of feedback loops and cascading dynamics in amplifying system-level risks. The results demonstrate that traditional static security controls are insufficient for managing risks in generative AI systems. Instead, an adaptive and evolving security approach is required to address the dynamic nature of these environments. In this context, the study proposes a multi-layered adaptive defense architecture incorporating context-aware access control, dynamic API governance, data flow restrictions, continuous monitoring, and real-time validation of model behavior. In conclusion, this research highlights that security in generative AI systems must be understood within the framework of complex system dynamics rather than static threat models. By integrating principles of complexity science into AI security analysis, this study provides a novel perspective for understanding and managing emergent risks in generative AI-enabled systems. The proposed approach contributes both conceptually and practically to the development of adaptive and resilient AI security frameworks.

Keywords: Generative AI, Complex Adaptive Systems, Emergent Risk, Adaptive Security, AI Safety, Web Security

Acknowledgments

This section could be omitted, in the case the authors don't wish to acknowledge any person or organization at this stage.

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Simulation of Cooperative Robot Navigation for Agricultural Tasks in Vineyard Environments

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Extended abstract

The automation of agricultural tasks using robots can offer a solution to problems arising from seasonal labor shortages and the increasing demand for agricultural output [1]. Several autonomous or semi-autonomous robot systems have been proposed and studied for various agricultural tasks, ranging from seeding and harvesting to crop monitoring and targeted plant protection [2,3,4]. Even though single-robot systems have been extensively studied, Multi-Robot Systems (MRS) can offer superior performance through parallelism as well as provide opportunities to extend the capabilities of individual robots by deploying heterogeneous robots for a particular task [4,5]. However, the introduction of multiple robots in a usually constrained environment, such as in tightly planted crops, can give rise to added complication in robot coordination, task and row allocation and collision avoidance.

The present study proposes a hierarchical control architecture for the cooperative navigation of homogeneous robots in a structured vineyard environment consisting of parallel rows. At the top level of this hierarchy, the system utilizes a central planner that employs a Breadth-First Search (BFS) algorithm for dynamic task assignment and strictly manages row access through a "Request-Response" protocol to eliminate deadlocks. While the global planning algorithm coordinates the general paths of the robots, the lower level of the hierarchy involves local control of the robots, where they employ GPS and LiDAR sensors for localization and reflexive obstacle avoidance.

More specifically, the proposed control architecture utilizes a topological map of the vineyard, which includes the lane topology and connections. The planner is also initialized with a list of coordinates of the points of interest, which are the locations that the robots must visit in order to carry out the desired task (e.g. harvesting). The planner is dynamically assigning routes to the robots by executing a Breadth-First Search (BFS) algorithm. Given the list of desired destinations, the algorithm iteratively builds a route by traversing neighboring lane connections, selecting only those whose lane group is currently not in use or reserved by another robot. The individual robots deployed are traversing the routes assigned to them and communicate their state to the planner at every point. When a robot reaches capacity (for example after harvesting), the planner recalculates the workflow for the return trip, assigning the remaining points of interest to the next available unit, in order to ensure continuous operation. The navigation to the next waypoint of the route is resolved by the local movement mechanism of each robot, based on current location and any obstacles present. The proposed control architecture was tested in a realistic virtual environment constructed in the Webots simulator, in which a virtual vineyard consisting of rows delineated by 3D grapevines was implemented. The robots chosen for the simulation studies were the Robotnik Summit-XL platforms, due to their physical characteristics and their sensory capabilities. Variants of these robots have previously been employed in agricultural robots' research [8].

The experiments that have been conducted are evaluating the performance of the proposed control architecture in a multi-robot coordination scenario. This performance was compared against the performance of single-robot navigation tasks as well as against experiments with other decentralized control scenarios. The experimental results demonstrate a 35% reduction in operation time compared to single-robot baselines, as well as superior stability compared to decentralized approaches, ensuring consistent workflow in narrow agricultural corridors.

Keywords: Agricultural robotics; Cooperative navigation; Planning; Task allocation; Precision Agriculture;

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Time-Dependent and Complex Structure of the Relationship Between Global Temperature Anomalies and Atmospheric CO₂

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Extended abstract

The climate system is a complex and dynamic structure shaped by the interaction of numerous variables. Accordingly, relationships between climate variables must be examined not only through contemporaneous linear approaches, but also by considering time dependency and system behavior. This study analyzes both the statistical and dynamic properties of the relationship between global temperature anomalies and atmospheric CO₂ concentrations [1, 2]. The analysis employs global surface temperature anomaly data (GISTEMP v4) provided by NASA and atmospheric CO₂ data published by NOAA [3, 4]. Datasets were merged on an annual basis and missing observations were removed. Pearson correlation analysis was applied and visualized through scatter plots. Autocorrelation analysis was conducted to investigate system memory, and lagged variables were used to test delayed effects. Entropy analysis was performed to quantify the system's complexity level, and phase space representation was used to examine structural properties of the time series. Future steps include stationarity tests, cointegration analysis, and causality tests. The results reveal a very strong positive relationship between atmospheric CO₂ and temperature anomalies ($r \approx 0.97$), with a clearly linear structure. Autocorrelation analysis indicates that temperature anomalies depend on their past values, confirming that the system carries a degree of memory. Lagged analysis shows that the effect of CO₂ changes on temperature persists over time. Entropy findings indicate that the system is not entirely random but contains a certain order and moderate complexity. Phase space representation shows largely linear behavior, with small deviations suggesting possible nonlinear dynamics [5]. This study demonstrates a strong co-movement between atmospheric CO₂ and temperature anomalies while showing that this relationship is not merely a simple linear structure. The findings reveal time dependency, lagged effects, and a certain level of complexity, supporting the view that the climate system exhibits complex behavior. Planned advanced analyses are expected to more comprehensively elucidate the long-term dynamics and structural characteristics of this relationship.

Keywords: Climate change; CO₂ concentration; Temperature anomalies; Nonlinear dynamics; Entropy analysis.

Acknowledgments

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A PINN-Type Framework for Cryptocurrency Price Forecasting with GBM-Inspired Constraints and Leakage-Safe Evaluation

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Extended abstract

Cryptocurrency price forecasting remains challenging due to high volatility, frequent regime changes, and market sensitivity to exogenous information [1]. The literature has also shown that evaluation can lead to overestimation of predictive power when strict temporal separation is not observed or when leakage occurs during parameter selection and model testing [2], [3], [4]. Based on the stochastic logic of Geometric Brownian Motion (GBM) [5], [6] and the general philosophy of Physics-Informed Neural Networks [7], this paper proposes a PINN-type framework for daily closing price forecasting, with emphasis on methodologically rigorous and reproducible evaluation [2], [3], [4].

The introduced methodology trains a multilayer perceptron on the daily logarithmic returns ($\Delta \log$) and reconstructs price levels multiplicatively. The term PINN is used here with an explicitly qualified meaning: no residual differential equation is directly solved; instead, mild regularization terms are introduced in the loss function so that the predictions remain close to the mean and variance of the training-set returns, in accordance with the basic logic of GBM [5], [6], [7]. The data are obtained from the CryptoCompare Data API [8]. The evaluation is organized through SAFE pre-data separation, with window selection performed exclusively within SAFE. A final holdout block and additional independent time blocks are used for stability checks when sufficient history is available. Walk-forward retraining is applied throughout, ensuring that the holdout is not used for tuning or exploratory selection [2], [3], [4].

The framework is applied to eleven cryptocurrencies with heterogeneous market behavior. In the final, strictly out-of sample holdout blocks, the reported FINAL PRICE% values range from approximately 89.69% to 95.95%, indicating stable price-level reconstruction within the controlled protocol of the study. However, in a separate forward-looking evaluation up to the end of the following month, the average MAPE is 37.9% (SD = 15.9%), the average closeness accuracy is 62.1% and the directional success is 54.5% (6/11). These findings suggest that the method can remain stable under strictly controlled out-of-sample evaluation, but this does not imply reliable predictive performance when market conditions change abruptly [2], [3].

The main contribution of the paper is methodological rather than a claim of universally superior predictive performance. A transparent and leakage-safe framework for theory-informed neural forecasting on non-stationary financial time series is proposed, with a clear distinction between SAFE calibration, holdout evaluation, and walk-forward control. The results indicate that mild GBM-type constraints can act as a form of structural regularization, while future research can extend the framework to additional baselines, regime-aware methods, and enriched input features.

Keywords: PINN-type models; Geometric Brownian Motion; cryptocurrencies; logarithmic returns; leakage-safe evaluation.

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Toward Programmable Chaos: A Digitally Reconfigurable Vilnius Oscillator

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Extended abstract

Chaotic oscillators have attracted sustained interest due to their rich nonlinear behaviour and wide applicability in secure communications, random number generation, sensing, and neuromorphic systems. Since the foundational developments of Chua's circuit and subsequent experimental realizations, research has focused on improving controllability, robustness, and practical integration of chaotic circuits [1]. Among these, the Vilnius chaotic oscillator, proposed by T.Tamasevicius and co-authors [2], provides a compact, experimentally validated platform that exhibits a broad spectrum of nonlinear regimes [3].

In this work, we propose a digitally controlled reconfigurable Vilnius oscillator, with emphasis on controlled selection of operation modes rather than conventional parameter tuning. The classical oscillator is extended by incorporating two actively controlled capacitors (C_{C1} , C_{C2}), an additional controlled voltage source (V_{C3}), and a digitally controlled resistor (R_{C4}) (see Fig.1). These elements are interfaced with a microcontroller unit (MCU), which generates digital control signals that define the effective circuit parameters in real time.

The key idea is to enable deterministic switching between distinct dynamical operation modes, such as chaotic and subharmonic periodic regimes, through discrete digital control. In contrast to traditional approaches that rely on continuous parameter sweeps and are sensitive to initial conditions, the proposed system introduces a structured framework in which the oscillator behaviour can be reproducibly configured via digital codes. This effectively transforms the nonlinear oscillator into a mode-programmable system, where each control configuration corresponds to a specific class of dynamical response. The methodology is validated through both circuit-level simulations and experimental implementation. Detailed SPICE simulations confirm the feasibility of controlled transitions between distinct dynamical operation modes across the targeted parameter space. Furthermore, a hardware prototype has been developed, integrating the MCU-based control layer with the reconfigurable analog circuitry. Experimental results demonstrate robust, repeatable switching between chaotic and subharmonic periodic regimes, confirming the practical feasibility of the proposed concept. In addition, the mode switching latency—defined as the transient interval required for the system to settle into a new dynamical regime following a parameter update—has been evaluated. The results indicate predictable and bounded transition dynamics, with no unintended intermediate behaviours observed.

The proposed approach is particularly relevant for applications in secure communications, where different dynamical regimes can be employed for synchronization-based encoding schemes and adaptive modulation strategies. Additional applications include hardware random number generation with controllable entropy sources, adaptive RF systems with reconfigurable nonlinear responses, and neuromorphic circuits that can emulate functional state transitions through mode switching. This work introduces a step toward digitally programmable nonlinear dynamics, bridging embedded digital control and analog chaos, and opening new directions for reconfigurable analog computing and chaos-based information processing.

Keywords: Bifurcations, Chaotic Oscillators; Digital Control.

Acknowledgments

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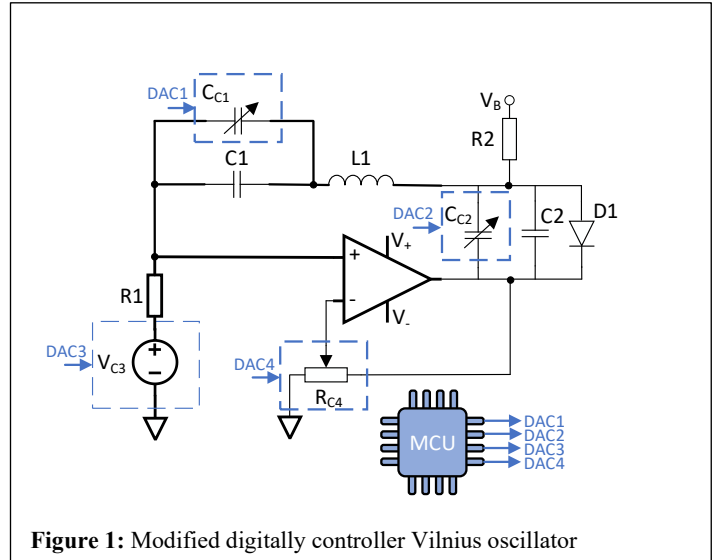


Figure 1: Modified digitally controller Vilnius oscillator

Bridging Deterministic Chaos and Uncertainty Quantification: Polynomial Chaos Approaches to the Largest Lyapunov Exponent

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Extended abstract

The largest Lyapunov exponent (LLE) is a fundamental diagnostic of chaotic behavior in nonlinear dynamical systems, as it quantifies the exponential divergence of nearby trajectories and the associated sensitivity to initial conditions. Traditional trajectory-based estimators, such as Benettin's method or Wolf's algorithm, remain the de facto standard, but they are often limited by noise sensitivity, high computational cost, and difficulties in scaling to high-dimensional systems. Recently, a variance-based approach has been introduced that estimates the LLE by tracking the exponential growth of ensemble variance under deterministic dynamics, implemented via intrusive polynomial chaos, thus providing a probabilistic counterpart to classical trajectory divergence.

Within this variance-based framework, the dynamic system evolves an initially localized probability distribution in the phase space, and the LLE is extracted from the asymptotic growth rate of the covariance, which is governed by the Liouville equation and the underlying flow map. The intrusive polynomial chaos formulation is obtained through a stochastic Galerkin projection of the governing equations onto a Hermite polynomial basis, resulting in a coupled deterministic system for the polynomial coefficients that directly encodes the evolution of statistical moments. In contrast, a non-intrusive formulation leaves the original solver unchanged and reconstructs the polynomial chaos representation from sampled trajectories (*e.g.* using quadrature or regression) which facilitates the treatment of complex or legacy codes at the expense of additional sampling effort.

In this work we present a simplified comparative study of intrusive and non-intrusive polynomial chaos formulations for variance-based LLE estimation on low-dimensional chaotic benchmarks, taking the intrusive methodology of García-Gutiérrez et al. [1] as the reference framework. Numerical experiments on canonical systems such as the Lorenz and Rössler attractors show that the intrusive formulation reproduces reference trajectory-based LLE values with high accuracy for moderate polynomial orders, while simultaneously providing access to the full covariance structure of the ensemble.

Comparative analysis indicates that variance-based LLE estimation via polynomial chaos offers a flexible framework that naturally *connects* deterministic chaos and the quantification of uncertainty. The intrusive approach is particularly attractive when the governing equations are accessible and a tightly coupled stochastic Galerkin solver can be implemented, whereas the non-intrusive alternative is better suited to black-box or industrial models, where only trajectory evaluations are available. These findings support the use of polynomial chaos-based variance growth as a practical and theoretically grounded tool for Lyapunov analysis and motivate further extensions to higher-dimensional systems, non-Gaussian uncertainties, and more complex chaotic flows.

Keywords: Lyapunov exponent; uncertainty quantification; polynomial chaos; stochastic collocation

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Digital Transformation of Public Service Forms: A Unified Platform for Citizens and Agencies in Greece

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Extended abstract

In the modern era of digitalization, the bureaucracy of Public Services continues to be an obstacle to technological development in many countries, such as Greece [1]. The submission of a request form by a citizen to an institution, as well as its completion, is usually a complex and time-consuming process [2]. Specifically, the major problem in Greece is that each public service uses a different tool through which it receives and serves requests, such as an information system, a digital form posted on the public service's website, a form for submitting fields, e.g., Google Forms or even worse, a photocopied request on paper. As a result, existing systems in Greece are currently transferring bureaucratic chaos to the digital world, creating confusion for both public servants and citizens.

To this end, this work proposes the holistic digital transformation of public service forms in Greece, aiming at the development of an operational integrated information system (IIS) which provides the ability to complete and submit public service forms and automatically collect all supporting documents.

The functionality of the proposed IIS is addressed to two categories of users: public servants and citizens. Through the proposed system, users without special information technology (IT) knowledge can log in with their official credentials and retrieve the template of a form required by a public service, can create their own template in case there is no official template provided, complete it and submit it to the respective service by also attaching required supporting documents retrieved by TaxisNet, Greece's official online platform of the Independent Authority for Public Revenue.

For the creation of new templates, the system provides a friendly user interface toolbox resembling a Word Ribbon, where each user can log in and simply click to select between a set of typically required fields, and necessary attached supporting documents. Moreover, the created template is published on the main page of the IIS so that it is available to other users who may need it. For example, if through the proposed IIS a municipality designs an application form for a sidewalk-use permission where 20 fields of information need to be filled in on the application and 10 files of necessary supporting documents must be attached, other municipalities with the same need can directly adopt and use/edit the already existing form.

Traceability of submitted forms is also available through the proposed system. After a form is submitted, users receive a feedback email of a copy of the submitted form, accompanied by a reference code used to monitor the status of their submitted request. Moreover, security is pursued; completed application fields with users' personal data, attached personal documents and retrieved private documents from TaxisNet are not accessible by other users of the system, while users' TaxisNet login passwords are not saved under any circumstances.

Expected outcomes of the proposed system include saving time and resources, and reducing complexity for the user, since a typical form would require a couple of minutes to be submitted and could be done individually without the need for support from professionals in the field. Currently, it takes much longer, while in cases, the increased complexity of non-integrated systems leads users to turn to accounting offices or to third parties familiar with IT systems.

Moreover, the proposed system aims to eliminate human error factors when completing official requests to public services, including incorrect or incomplete submissions of required supporting documents. Digital transformation pursued through the proposed system would also lead to the reduction of the environmental footprint due to zero printing. Finally, the proposed system aims to unify all information systems for filling in application fields and submitting public forms, exponentially reducing State expenditures for the purchase and maintenance of multiple and non-integrated form submission systems.

Overall, the proposed integrated IIS demonstrates how a unified, secure and reusable digital framework can significantly streamline public service workflows, reduce bureaucracy, and accelerate the digital transformation of the Greek public sector.

Keywords: Digital transformation; Process complexity; Public service forms; Integrated information system; Digital public services

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A Comparative Evaluation of Deep Learning Models (LSTM, TFT, ESN, MAML) for Forecasting Bitcoin and S&P 500 Time Series

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Extended abstract

This study investigates the analysis and forecasting of financial time series using advanced machine learning techniques, with a focus on Bitcoin as a representative of the cryptocurrency market and the S&P 500 index as a benchmark for traditional financial markets. The data utilized in this study extends from September 15, 2014, to November 24, 2025, capturing diverse market conditions and fluctuations in volatility. The proposed approach examines a range of state-of-the-art models, including Long Short-Term Memory (LSTM) networks, Temporal Fusion Transformers (TFT), Echo State Networks (ESN), and Model-Agnostic Meta-Learning (MAML). These approaches are primarily based on neural network architectures, particularly recurrent neural networks (RNNs), for effective modeling of sequential data. Their predictive performance is evaluated using widely adopted metrics, including Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and the coefficient of determination (R^2). The results indicate that MAML demonstrates superior predictive performance, achieving lower error metrics and higher R^2 , likely due to its adaptability to dynamic temporal patterns. LSTM exhibits competitive performance, effectively capturing overall trends, though with comparatively lower accuracy.

KeyWords: Deep Learning, Financial Time Series Forecasting, Bitcoin, S&P500,

Real-time AI-powered moving pattern detection from low-cost accelerometer and gyroscope data

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Extended abstract

We are developing a real-time AI framework for recognizing short, gesture-like motion patterns from smartphone sensors (or sensor-enabled gadgets, like rings, bands, or bracelets) [1, 2]. We make use of accelerometer and gyroscope data, collected from built-in IMUs, to identify custom-recorded gestures, such as rotations, tilts, and swings [3, 4].

A GRU Neural Network is used as a core model, leveraging its capability to model temporal dependencies in sequential data with reduced computational complexity, compared to LSTM and Transformer NNs. A scalable GRU NN is trained on demand to detect one or several pre-recorded gestures and deployed on the user device for real-time inference. Full or partial gesture detection is notified with minimal latency, with a quantitative indication of the completion percentage.

The system architecture integrates lightweight preprocessing and normalization to ensure high responsiveness and low energy consumption and cost. Preliminary experimental results, with mid-range commercial smartphones, demonstrate accurate recognition of two motion patterns, sampled at 50 Hz, with minimal latency, confirming the feasibility of edge AI for motion understanding, without cloud dependence.

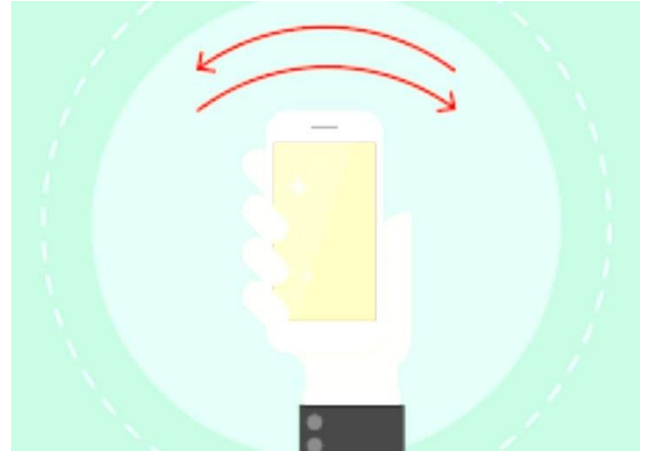
Potential applications include all contexts in which gesture-based control can improve human-machine interaction, among which gaming, home automation, and trade fair and museum navigation, connected vehicles, mobility services, and intelligent transport systems.

Despite this potential, existing motion recognition approaches face several challenges and are limited to the classification of typical gestures [5, 6]. Many models are trained offline on curated datasets and rely on cloud-based inference, leading to latency, bandwidth consumption, and privacy concerns in real-time embedded applications [7]. Moreover, inertial measurement unit (IMU) data from smartphones is often noisy, subject to drift, and varies significantly across devices and users [8]. As a result, classical machine learning methods struggle to generalise in unconstrained, real-world environments and fail to meet the computational and latency requirements necessary for real time edge deployment.

Keywords: Inertial Measurement Unit (IMU); Gated Recurrent Unit (GRU); accelerometer, gyroscope; edge AI.

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Reliability Analysis of Consecutive k-out-of-n Systems Based on Lyapunov Exponent: A Wind-Induced Stress Case Study

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Extended abstract

Reliability of complicated engineering systems such as telecommunication infrastructure, pipeline network and electronic transmissions are widely modelled by consecutive k-out-of-n systems [1]. When the applied stress exceeds the capacity of a component to resist that stress, under the so-called stress-strength framework [4, 5], the system is defined as failed. Traditional estimation techniques, especially those based on the proportional hazard rate family, usually assume stress and strength are stationary random variables described by fixed parameters [2, 3]. However, many quasi-linear dynamic operating conditions are nonlinear in practice where the stress variable traces deterministic but inherently unpredictable paths. In the present context, however, the reliability function behavior over parameters space is a crucial issue that has been overlooked in literature. As positive Lyapunov exponents are a standard measure of chaos in nonlinear dynamical systems [6], they provide a principled method for assessing the sensitivity of reliability estimates to perturbations in dynamic stress environments.

In this work, a framework is proposed for studying the reliability of consecutive k-out-of-n systems defined in a stress-strength context subjected to nonlinear dynamic loads based on chaos theory. In such a formulation, stress is treated as the output path of a nonlinear dynamical system and the corresponding reliability function is computed over parameter space instead of as a fixed scalar quantity. Numerical Lyapunov exponents aid in identifying parameter stability regions, transitional behavior, and reliability instability. Parameter configurations corresponding to regions with positive Lyapunov exponents can be considered as a sensitivity map. In this map, extremely small deviations around these regions can lead to significant degradations in reliability estimates at the data or parameter level. In contrast, configurations with negative Lyapunov exponents represent more stable and reliable regions in terms of statistical inference.

The maximum likelihood and Bayesian estimation approaches are comparatively assessed in the context of Weibull-based modeling of component strength within the recognized instability regions. Monte Carlo simulation experiments show that frequentist estimators become more fragile as the underlying stress dynamics converge on chaotic behavior, while Bayesian approaches especially those using informative prior distributions lead to more stable inference results.

The proposed methodology is illustrated through a case study of wind-induced loading on power transmission line structures. Through this process, scenarios in which time-dependent wind loading creates dynamic stresses in successive structural elements can be identified. Thus, operational regimes where traditional reliability assessment approaches lose their validity can be determined. The results show that incorporating Lyapunov-based susceptibility diagnostics into reliability analysis can significantly improve inference accuracy in systems exposed to nonlinear environmental loads and effectively support risk-based engineering decision-making processes.

Keywords: Lyapunov exponent; Consecutive k-out-of-n system; Chaotic sensitivity; Stress-strength reliability; Bayesian estimation; Wind-induced stress.

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Self-organized locomotion generation for hexapods

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Extended abstract

Generating robust and *adaptable* legged locomotion using minimal control architectures remains a central challenge in bio-inspired robotics. Many existing approaches based on *central-pattern generators* (CPGs) depend on multi-neuron oscillatory networks, asymmetric coupling schemes, abstract phase representations, or task-specific parameter tuning to achieve stable *gait patterns*. In this work, we propose a minimal sensorimotor control framework that relies on single-neuron CPG units combined with *proprioceptive feedback*. Through theoretical stability analysis of the dynamical system and real-world robotic experiments, we demonstrate that fully symmetric coupling among these simple units is sufficient to produce self-organized tripod-like gaits.

The *multistability* of the proposed system supports reliable gait transitions through a simple single-pulse “kick” control mechanism and maintains stable locomotion even in the presence of leg failure, highlighting its robustness. In the strong attractor regime, coordinated movement emerges without the need for intrinsic neural oscillations, being driven entirely by sensory feedback. This finding challenges the assumption that internal oscillatory dynamics are necessary for rhythmic locomotion. We analyze the experimentally measured leg positions through different quantitative metrics, such as the *phase locking values* (PLVs) of the robot’s leg pairs, and then numerically classify them into different gait patterns.

The same control architecture, without any parameter modification, can also generate coordinated locomotion in quadruped systems, demonstrating the generality and scalability of the approach. Overall, our results show that complex, stable, and *adaptive* locomotor behaviors can emerge from simplified, *decentralized* control mechanisms.

Keywords: self-organization, pattern formation, locomotion, adaptation, hexapod

Acknowledgments

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Practical Variational Optimisation for Invariant Solutions to Turbulence

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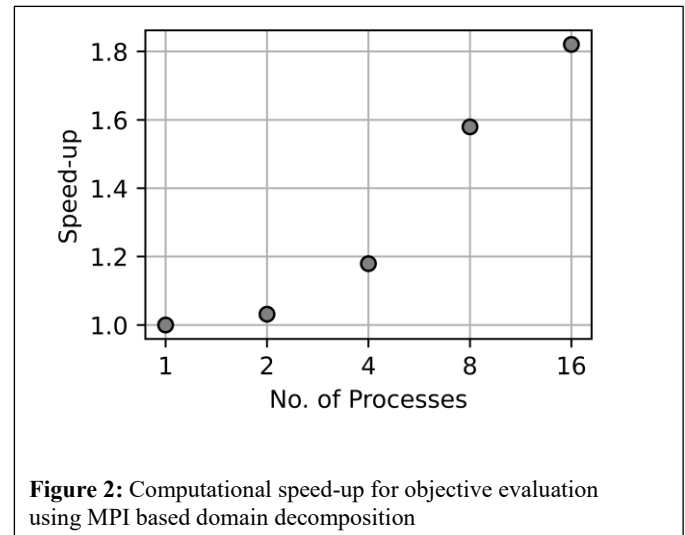
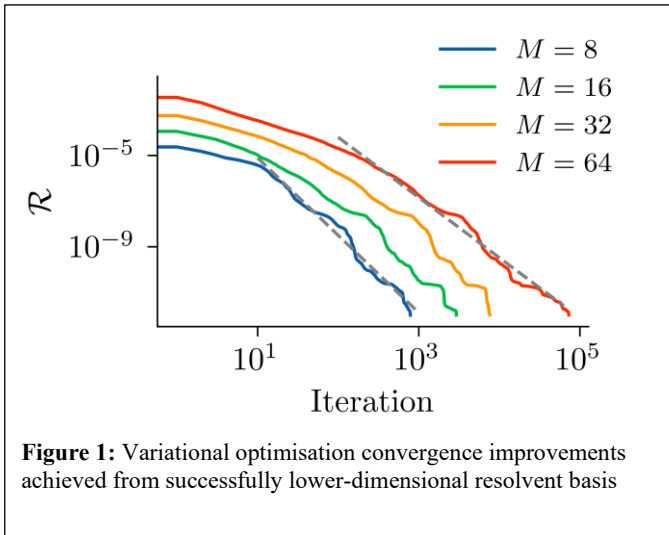
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Extended abstract

Invariant solutions embedded in strange attractors provide a skeleton upon which chaotic dynamics can be organised, allowing the prediction of ergodic properties^[1]. In this framework, Exact Coherent Structures (ECSs) are the focus of study, as they have been linked to important dynamical processes in wall-bounded turbulence and can be used to approximate statistics^[2]. However, current methods available to numerically determine these solutions are difficult to apply due to the high dimensionality of the problem, along with the sensitive dependence on initial conditions. Together, these impose significant restrictions on the practical computation of ECSs, as well as limiting the time horizon for solution searches. Therefore, it is prudent to explore methods that are amenable to low-dimensional representations, coupled with a robustness that guarantees convergence even for sub-optimal initial guesses.

The variational optimisation^[3] methodology is a robust algorithm for finding ECSs. When coupled with a Galerkin projection step using a basis derived from resolvent analysis^[4], a general method for finding ECSs in wall-bounded flows is obtained. The addition of the projection step also naturally integrates a reduced-order model into the solution procedure. It is shown, via analysis of the Hessian matrix of the optimisation problem, that resolvent analysis provides an optimal basis for preconditioning the optimisation problem, thereby improving convergence rates (figure 1). The projection step, however, comes at the cost of storing the basis in memory, which itself scales poorly with increasing problem size (Reynolds number, time horizon, etc.). The second key component of this work is the exploration and implementation of flexible parallelisation schemes that can exploit heterogeneous HPC resources. This is achieved via domain decomposition methods using MPI (figure 2) to distribute data across multiple processes, coupled with GPU acceleration to reduce execution time.

The methods developed are demonstrated on plane Couette flow. To assess the efficiency of the proposed framework particular attention is given to the trade-off between memory requirements and convergence behaviour, highlighting the practical limits of the approach. These results provide insight into the scalability of the method and its applicability to more complex turbulent flow configurations.



Keywords: Variational optimisation, turbulence, resolvent analysis, MPI, GPU

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Chaos-Aware Predictive Anomaly Detection in Complex Systems: Hybrid Statistical-Machine Learning Framework

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Extended abstract

Under varying conditions of operation, complex engineering and natural systems can progress from regular to irregular behavior [1]. Identifying such transitions before they evolve into major systemic breakdowns continues to pose a classical challenge for both predictive maintenance and risk management. Traditional anomaly detection methods have some efficacy in detecting abnormalities, but fail to capture how system dynamics shift and outpace predictability over time, especially when systems feature interdependence on multiple dimensions [2]. The direct incorporation of chaos-theory-based indicators into predictive models is still an underexplored approach. This enables the identification of not only abnormal events, but dynamic transitions that lead to such events as well.

We propose a hybrid statistical-machine learning framework for predictive anomaly detection in complex systems using chaos-aware feature engineering. The crucial assertion is that the shift from stable dynamics to chaotic dynamics can be regarded as an early warning sign of the imminent failure of any system. In order to quantify these transitions, time-series data are analyzed using nonlinear dynamical measures like the largest Lyapunov exponent, correlation dimension and Kolmogorov-Sinai entropy [3]. The features obtained from the chaos approach are fused with standard statistical and state-space features and then integrated into a hybrid prediction architecture that joint change-point detection and machine learning classification.

Monte Carlo experiments on both artificially generated chaotic systems and benchmark datasets are conducted to analyze the proposed framework. Artificial time series obtained by using well-known nonlinear maps, whose bifurcation parameters can be directly controlled, enable systematic investigation of stable, transitional and fully chaotic regimes. The results indicate that chaos-theoretic-enhanced models outperform purely statistical descriptive-based models or raw time-series representations in terms of early-predictive capabilities. The hybrid framework achieves especially high accuracy for transitional regimes, where timely intervention is most important.

One case study further illustrates how the framework can be deployed in monitoring scenarios where dynamical instability might occur before observable failure. The application of chaos theory together with predictive anomaly detection represents a paradigm-shift in our efforts to go beyond the black-box pattern-recognition mindset and develop an interpretable understanding of dynamic mechanisms that prompt anomalous behavior [4]

Keywords: Chaos theory; Keywords: Anomaly detection; Lyapunov exponent; Hybrid predictive model; Complex systems; Machine learning.

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Opinion dynamics in activity-driven voter models on heterogeneous networks

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Extended abstract

In social networks, agents are not permanently engaged but display heterogeneous activity patterns with periods of high and low participation. These temporal patterns shape opinion dynamics, where, in a binary setup, agents hold one of two opposing positions on a given topic. Typically, topics generate bursts of activity that later decay as interest fades. However, most opinion dynamics models are implemented on static interaction networks, where any agent can update their opinion according to the opinions of their neighbors [1]. Classical models such as voter models based on imitation predict consensus and opinion polarization. Different approaches have been proposed to capture how network structure affects the dynamics, for example in the time required to reach consensus. One of the simplest and most successful ones is the degree based approach [2], where the consensus time depends on the first moments of the degree distribution.

Here we study opinion dynamics on heterogeneous networks when agents differ not only in the opinion they hold, but also in whether they are active enough to express it. We introduce a coupled model in which each node carries a binary opinion and an activity state. Opinion updates follow voter-like imitation, but only active agents can participate in interactions. Activity spreads and decays through an SIR-like contagion process [3] on the same network. Figures 1–3 show a typical realization of the dynamics on a small heterogeneous network (N=200), from the initial state to peak activity and the final state. Initially, two hubs with the same opinion are active and spread both their opinion and their activity to their neighbors. As activity eventually dies out, the opinion of the initially active nodes predominates in the final state, while consensus is not reached, unlike in the classical voter model.

Using a heterogeneous mean-field description and stochastic Gillespie simulations on homogeneous and heterogeneous topologies, we analyze how the coupling between activity and imitation shapes the collective dynamics. We show that the final opinion outcome depends not only on the initial opinion fractions, but also on their distribution among the active population. In particular, the opinion initially overrepresented among active agents is systematically favored. Because activity is transient, the ordering process can be interrupted before consensus is reached, leaving the system in frozen coexistence states absent in the standard voter model. These results show that temporally varying participation and network heterogeneity can strongly bias opinion formation and alter the route to consensus.

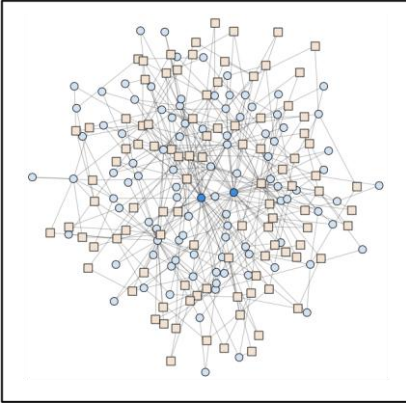


Figure 1: Initial opinion–activity state. Squares (orange) denote opinion 0 and circles (blue) opinion 1. Light shading indicates susceptible (inactive) nodes, and medium shading infected (active) nodes.

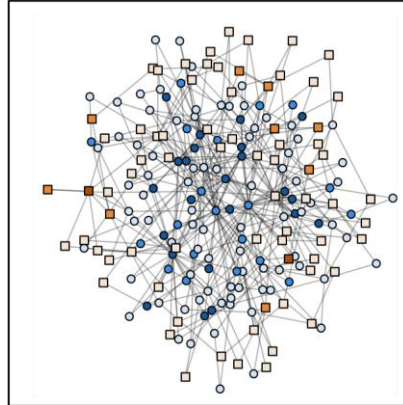


Figure 2: Peak activity state. Dark shading indicates removed (inactive) nodes.

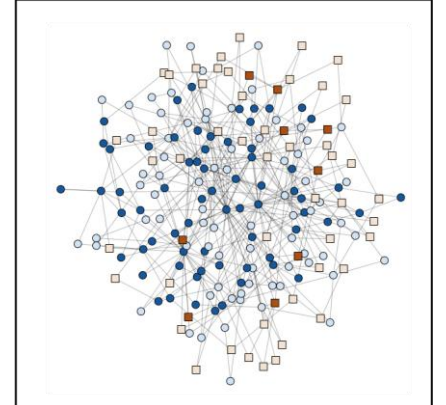


Figure 3: Final state. Opinion dynamics stops and the system remains in a frozen coexistence state.

Keywords: Opinion dynamics; Activity patterns; Voter model; SIR model

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The building blocks of 3D models of barred galaxies

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Extended abstract

The orbital study of Milky Way like models of barred galaxies of three degrees of freedom help us to detect the orbits that support different structures of the galaxies like rings and spiral arms. A parametric study is done regarding the strength of the bar's perturbation Q_f from 12% and up to 60% in forces, which is the range of values that covers almost the entire range of bar's perturbation of the corresponding values observed in real barred galaxies (see Laurikainen et al. 2004 and Buta et al. 2009).

The study is made with the help of 4D Poincaré surfaces of section (PSS) of the 6D phase space of the system in different energy levels. In order to detect the different structures supported by sticky chaotic orbits the method of the apocentric sections of the manifold theory (introduced by Voglis et al. 2006 and Romero-Gómez et al. 2006) is used for orbits with initial conditions above the unstable manifolds of the planar $PL_{1,2}$ family of orbits, having a small initial component on the z -axis. The planar $PL_{1,2}$ orbits are the continuation of the unstable Lagrangian points $L_{1,2}$, for energy levels E_n greater than the $E_{nL_{1,2}}$.

We conclude that in all models with different bar's perturbation different morphological structures are supported by 3D sticky chaotic orbits in different energy levels like the envelope of the bar, outer rings of R_1 type and spiral arms. Ring structures are mostly supported for smaller values of the bar's perturbations Q_f (where the spiral arms are not supported by 3D orbits). On the other hand spiral arm structures are supported for larger values of Q_f . We find hyper surfaces (in the 4D PSS) along which the 3D chaotic orbits that support the galactic structures are sticky for very long times before escaping from the system. Finally we determine the stickiness time of these orbits using the time evolution of the Finite Time Lyapunov Characteristic Number (FT-LCN). This time corresponds in many cases to many Hubble times and as a consequence these sticky chaotic orbits behave practically as regular ones during the life time of the galaxy.

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Lagrangian Coherent Structures and the heteroclinic transport of small bodies in the solar system: a fresh approach to a classical problem

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Extended abstract

Traditionally defined through the 'ridges' of the finite-time Lyapunov exponents (FLI), the Lagrangian Coherent Structures (LCSs) trace the union of stable and unstable manifolds of any low-dimensional invariant object in the phase space of an autonomous dynamical system. The talk will refer to recent results in collaboration with Alessia Guido (U.Trento - U.Rome Tor Vergata) regarding the applicability of the LCS to a classical problem in Celestial Mechanics, namely the chaotic transport of small bodies (asteroids or Jupiter-family comets) throughout the entire chaotic domain formed by the overlapping of the all Mean Motion Resonances (MMRs) from 2:1, through the co-orbital and up to the 1:2 resonance. We will discuss how modern techniques allow to visualize the intricate network of heteroclinic connections between the manifolds emanating from all these resonances, thus interpreting the phenomenon of 'resonance hopping' observed for many real objects in this zone of the Solar System.

Keywords: Lagrangian Coherent Structures - Chaotic Indicators - Solar System Dynamics

Learning Nonlinear Grad-Shafranov Equilibria with Physics-Informed Kolmogorov-Arnold Networks

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Extended abstract

Tokamaks are toroidal devices for the magnetic confinement of thermonuclear plasmas through the use of strong magnetic fields. Tokamak plasma equilibria arise from the nonlinear balance between pressure-gradient forces and magnetic forces, reflecting strongly coupled interactions within the underlying Magnetohydrodynamics system and are described by the Grad-Shafranov (GS) equation, a nonlinear elliptic PDE whose solution landscape becomes increasingly more complex in the presence of steep pressure gradients. In this work, we use equation-driven, unsupervised deep learning to construct axisymmetric magnetohydrodynamic plasma equilibria with tokamak-relevant characteristics by solving the fixed-boundary GS problem. The equilibria are represented through Physics-Informed Kolmogorov-Arnold Networks, which approximate GS solutions while satisfying the appropriate boundary conditions, extending previous work based on standard Multi-Layer Perceptrons (Kaltsas and Throumoulopoulos 2022). We construct Solovev, linear, and nonlinear equilibria, including cases with a pressure pedestal (e.g., Fig. 1). Due to the increased nonlinearity of pedestal equilibria, a curriculum-learning strategy was required: starting from a network trained on a simpler equilibrium and gradually deforming the profiles so the network accommodates the desired complexity. This study demonstrates the capability of equation-driven, unsupervised deep learning to solve highly nonlinear PDEs with complex solution structure and highlights the importance of transfer learning for this task.

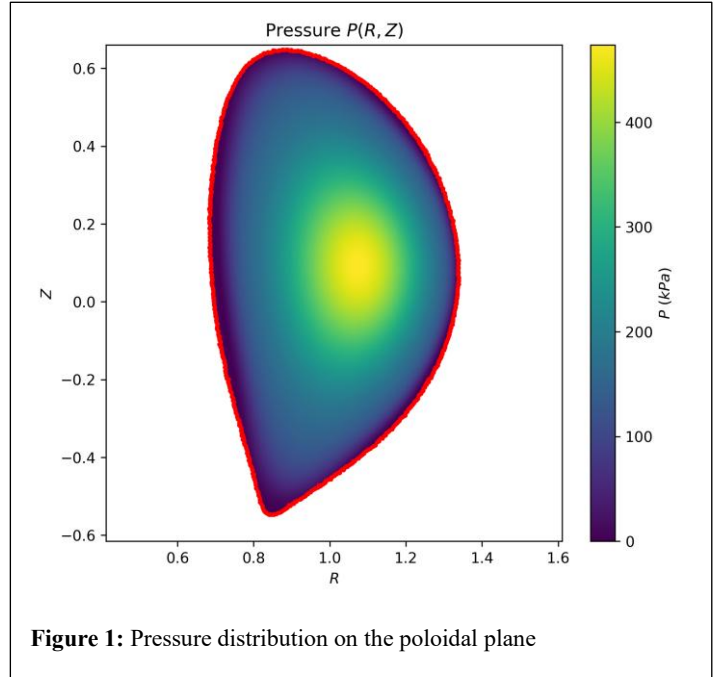


Figure 1: Pressure distribution on the poloidal plane

Keywords: Tokamak equilibria, Grad-Shafranov equation, Kolmogorov-Arnold Networks, Pressure pedestal, Curriculum learning

Acknowledgments

The contributions of D.A.K., A.I.K. and G.N.T. were carried out within the framework of the participation of the University of Ioannina in the National Programme for Controlled Thermonuclear Fusion of the Hellenic Republic.

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Influence of Annealing Temperature on Dielectric Properties of Magnesium Ferrite Nanoparticles for Energy Storage Applications

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Extended abstract

In recent years, spinel ferrites have attracted significant attention due to their promising magnetic and electrical properties, which make them suitable for applications in various fields such as energy storage systems, sensors, catalysis, and biomedical applications [1-4]. One of the most critical factors affecting the structural and functional properties of ferrites is the annealing temperature applied after the synthesis process. The annealing treatment reduces structural defects and improves phase purity; it also influences cation distribution, grain size, porosity, and internal stresses, leading to remarkable changes in dielectric and magnetic properties of the ferrite materials.

In this study, magnesium ferrite nanoparticles, which are regarded as a favorable spinel ferrite due to their low toxicity and biocompatibility [5], were synthesized via the hydrothermal method. The hydrothermal method is preferred due to its advantages, such as simplicity, low cost, and non-toxic processing conditions. Their structural and dielectric properties were investigated at two selected temperatures. The crystal structure was characterized by X-ray diffraction (XRD); chemical functional groups, and fingerprint characteristic bands were analyzed by Fourier transform infrared spectroscopy (FTIR); and dielectric properties were investigated using impedance spectroscopy technique. The results showed that magnesium ferrite nanoparticles with a nanometer size, cubic spinel structure, and characteristic tetrahedral and octahedral bonds were successfully synthesized at both annealing temperatures. The dielectric behavior of the nanoparticles was investigated in terms of complex dielectric function, complex impedance, and AC conductivity as a function of frequency. It was observed that the dielectric parameters exhibit high values at low frequencies and decrease rapidly with increasing frequency, eventually becoming nearly frequency-independent at higher frequencies. Moreover, it was seen that as the frequency increases, electrons cannot follow the alternating electric field, and electron hopping between conductive grains becomes the dominant mechanism with leading to a decrease in polarization. This behavior is consistent with the Koops model and can be explained by Maxwell–Wagner type interfacial polarization. Accordingly, magnesium ferrite exhibits an inhomogeneous dielectric structure consisting of highly conductive grains separated by poorly conductive grain boundaries. Furthermore, the effects of annealing temperature on crystallite size, lattice parameters, phase purity, and spinel metal-oxygen bonds were analyzed along with the dielectric properties, allowing the determination of the optimum annealing temperature.

In light of the results, the synthesized magnesium ferrite nanoparticles exhibited promising dielectric properties. In this context, the most suitable synthesis conditions had been identified, and owing to their remarkably high dielectric parameters, these materials were suggested to have potential applications in various dielectric systems, particularly in energy storage devices such as batteries and supercapacitors.

Keywords: Ferrite; Hydrothermal synthesis; Annealing; Dielectric properties; Impedance spectroscopy.

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Organizational Resistance in Digital Transformation: A Conceptual Analysis from a Complex Systems Perspective

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Extended abstract

Digital transformation has become one of the most significant organizational agendas in recent years; however, the outcomes of transformation efforts often differ considerably even under similar technological conditions. While digital initiatives are generally introduced through planned managerial decisions, the implementation process rarely progresses in a fully predictable manner. Organizational actors respond to change through local interpretations, existing routines, communication practices, and varying levels of adaptation, all of which influence the direction of the transformation process. In this context, resistance cannot be understood only as an explicit opposition to technological change; it also appears through subtle delays, selective compliance, hesitation, and the continuation of established work habits. This study examines organizational resistance during digital transformation from a complex systems perspective and aims to conceptually explain how local organizational reactions generate broader systemic consequences through nonlinear organizational interactions. The study is based on an integrative conceptual review supported by thematic interpretation. Literature focusing on digital transformation, resistance to change, organizational adaptation, and complex systems was examined comparatively in order to identify recurring conceptual patterns. During the analysis, concepts such as uncertainty, adaptation, feedback loops, self-organization, and emergence were used as interpretive anchors for understanding organizational behavior under transformation conditions. The findings indicate that resistance is not always stable or uniform; rather, it changes according to internal interactions and managerial responses that evolve during implementation. It is also observed that even limited managerial interventions may create effects beyond their immediate targets, generating new forms of adaptation or additional uncertainty in different parts of the organization. These observations suggest that digital transformation should be evaluated not only as a technical process but also as a dynamic organizational environment shaped by nonlinear interactions. By combining organizational change literature with complexity-oriented interpretation, the study offers a conceptual contribution for understanding how resistance develops and why transformation outcomes often remain difficult to predict.

Keywords: Digital transformation; Organizational resistance; Complex systems; Conceptual review; Organizational adaptation.

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Emergent Module Dominance in University LMS Ecosystems: A SelfOrganization Perspective

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Extended abstract

Introduction. Learning Management Systems (LMS) increasingly operate as complex digital environments in which repeated local interactions may generate institution-specific structural regularities beyond formally designed pedagogical frameworks. Although universities frequently employ technically comparable LMS infrastructures, institutional usage distributions often diverge over time, suggesting that digital learning environments may evolve through decentralized adaptive processes rather than uniform instructional logic.

Theory and Scope. This study examines whether recurrent module-level activity within university LMS environments gives rise to emergent dominant structures under equivalent technological conditions. Using aggregated institutional usage data obtained from five universities across two academic periods, the study focuses on four core LMS modules: content, assignment, quiz, and live session, together with active student and active course counts as contextual structural indicators.

Complex Systems Perspective. Within the framework of complex systems theory, LMS environments are conceptualized as adaptive institutional ecosystems in which localized digital actions accumulate into broader usage regularities without direct central coordination. The analysis explores whether specific modules consistently attain dominant positions within institutional usage patterns and whether such dominance may be interpreted as evidence of self-organizing digital equilibria.

Expected Analytical Direction. Institutional divergence is approached not as random variation but as a potential indicator of emergent equilibrium formation under identical technological constraints. Conceptually, content and assignment modules are expected to constitute the structural core of LMS interaction, whereas quiz and live session modules may display greater temporal sensitivity depending on institutional academic rhythms and local pedagogical adaptation. The study relies exclusively on anonymized aggregate institutional data and does not include individual user identification.

Keywords: LMS analytics; emergence; self-organization; complex systems; digital learning ecosystems

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Semi-static Memristive Behavior of a multifilament OEET

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Extended abstract

Memristor represents the fourth fundamental circuit element, characterized by a history-dependent resistance state [1]. Integration of memristive devices into flexible organic electronics opens new pathways for the development of wearable biosensors and neuromorphic computing systems. This study investigates the memristive behavior of an Organic Electrochemical Transistor (OEET) with an easily reproduced implementation within conventional fabrics, highlighting the potential for future implementation of textile-based, large- electronics with advanced computing functionalities [2]. OEETs utilize ion transport from an electrolyte into the bulk of an active material, driven by gate modulation, resulting in the electrochemical modulation of the channel conductivity [3].

The studied device (Fig. 1) consists of two high-density polyethylene (HDPE) yarns pretreated with the conductive PEDOT: PSS polymer to serve as either the gate or the channel, and a photocurable electrolyte based on a poly (-ethylene glycol) diacrylate (PEGDA) polymer matrix. The primary objective was to evaluate the device's nonlinear, historydependent electrical characteristics under varying static conditions – specifically gate voltage and measurement time delays – to confirm its functional memristive nature.

The electrical characterization was performed utilizing a Keysight B1500A Semiconductor Device Analyzer connected to a four-probe station within a Faraday cage, ensuring high-precision, low-noise measurements. The experimental protocol focused on capturing current-voltage (I-V) characteristics by applying a DC voltage sweep across the Source-Drain terminals (from -5 V to +5 V) under different constant Gate voltages (ranging from -2 V to +2 V). To map the timedependent ionic dynamics and trapping-detrapping processes, the time delay between measurement steps was systematically varied from 0 to 5 seconds. Scans were conducted in 300 step-sets (Fig.2), alongside high-resolution extended measurements of 5000 step-sets (Fig.3) to observe low-rate hysteresis growth and steady-state transitions.

The obtained I-V curves demonstrated clear memristive behavior, strongly dependent on both the applied gate voltage and the temporal measurement parameters [4]. For zero or minimal delay (0–1 s), the device exhibited near-ohmic behavior with negligible hysteresis, indicating that the ionic movement mechanisms lacked sufficient time to fully manifest. However, as the delay increased (2–5 s), pronounced pinched hysteresis loops emerged, particularly under positive gate bias (+1 V, +2 V). This dynamic response confirms that conductivity modulation is driven by the progressive doping and dedoping of the PEDOT: PSS channel by the electrolyte ions.

Experimental results validate the functionality of the PEDOT: PSS-based OEET as a reliable and tunable organic memristor. The strong dependence of the hysteresis loop on the measurement time delay proves that the internal resistance state is governed by slow ionic dynamics. Operating at low voltages and fabricated with low-cost, flexible materials, this organic memristor presents a highly viable platform for future applications in smart textiles, bio-signal processing, and energy-efficient neuromorphic computing architectures [5]. Future research will focus on optimizing fabrication parameters and materials to achieve tunable memristive behavior and enhanced device performance.

Keywords: Organic memristor; OEET; PEDOT: PSS; Hysteresis; Neuromorphic computing.

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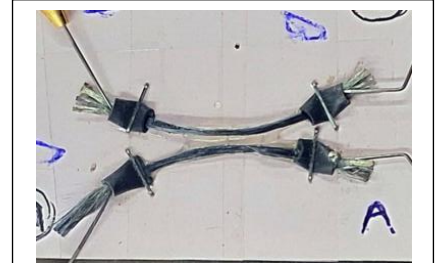


Figure 1: Multifilament OEET experimental prototype

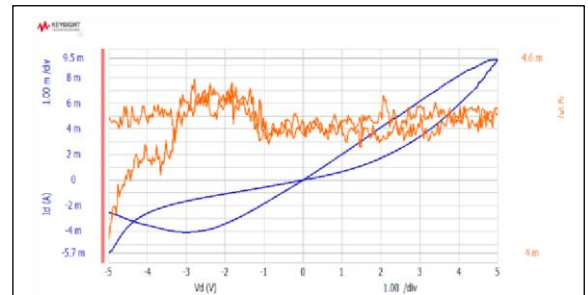


Figure 2: I-V characteristics measured at $V_G = +2$ V with 300 sweep steps and step delay 5 s

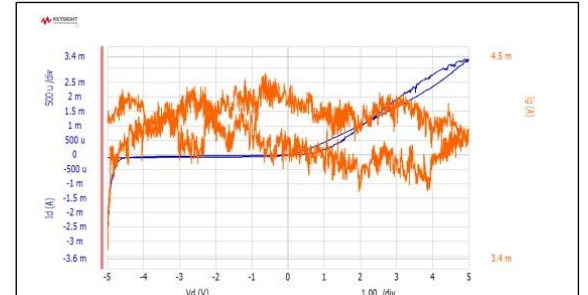


Figure 3: I-V characteristics measured at $V_G = +2$ V with 5000 sweep steps and step delay 5 s

[6]

Inhibitory Circuit Motifs Govern Cross-Frequency Directionality in Neural Networks

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Extended abstract

Cross-frequency coupling (CFC), particularly theta–gamma interactions, organizes neuronal firing during memory and cognition. While classical views assume slow oscillations modulate faster rhythms, cross-frequency directionality (CFD) measurements reveal bidirectional interactions, including cases where gamma precedes theta phase.

We investigate the mechanisms underlying theta–gamma directionality using a biophysically grounded computational model based on two canonical inhibitory motifs: Interneuron Network Gamma (ING) and Pyramidal-Interneuron Network Gamma (PING), both driven by an external theta input (see Figure). In the θ -ING configuration, feedforward recruitment of fast-spiking interneurons generates gamma oscillations. In the θ -PING configuration, gamma emerges via feedback interactions between pyramidal cells and interneurons. CFC was quantified using mean vector length, and directionality using the phase slope index-based CFD metric.

We find that directionality critically depends on the balance between feedforward and feedback inhibition. θ -ING motifs exhibit negative CFD (gamma-to-theta), whereas θ -PING motifs show positive CFD (theta-to-gamma). In mixed circuits, directionality changes smoothly as synaptic strengths vary within biologically plausible ranges. Importantly, more negative CFD values are associated with higher gamma peak frequencies, reflecting stronger feedforward recruitment of fast interneurons.

These predictions were validated using hippocampal recordings from rats exploring familiar and novel environments. Novelty was associated with more negative CFD values and higher gamma frequencies, and a significant correlation between CFD and gamma peak frequency was observed across animals.

Functionally, inhibitory balance defines computational mode: PING-shifted states favor transmission of afferent theta-driven inputs, whereas ING-shifted states broaden temporal windows for parallel input routing. Thus, cross-frequency directionality reflects inhibitory motif dominance and flexible information routing rather than a fixed oscillatory hierarchy.

Keywords: Cross-frequency directionality; Theta–gamma interactions; Inhibitory circuit motifs; Feedforward and feedback inhibition; Hippocampus.

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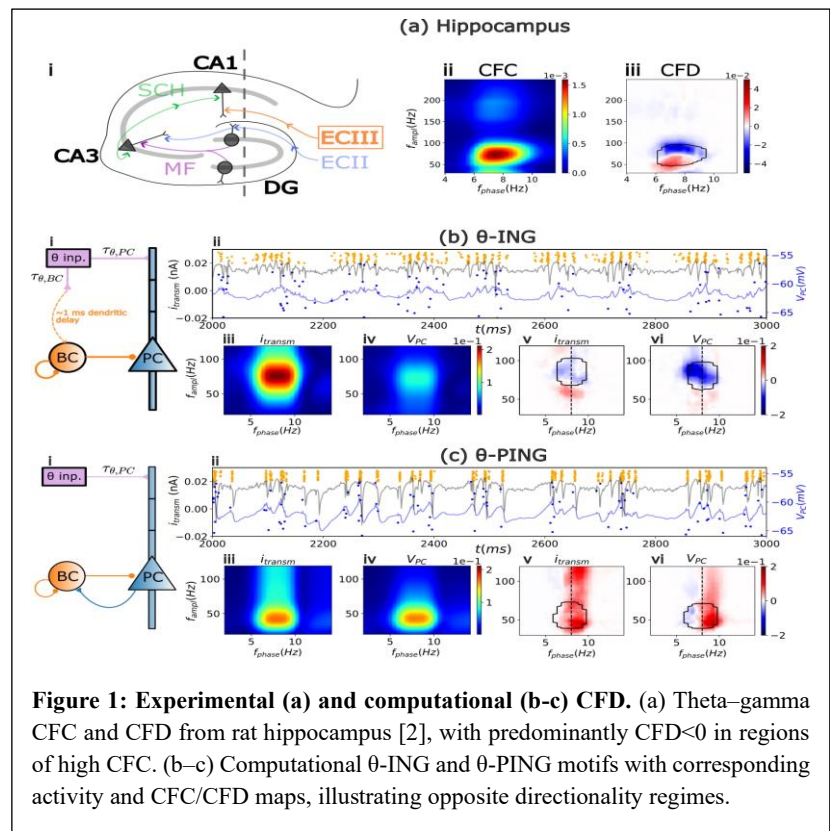


Figure 1: Experimental (a) and computational (b-c) CFD. (a) Theta–gamma CFC and CFD from rat hippocampus [2], with predominantly CFD<0 in regions of high CFC. (b–c) Computational θ -ING and θ -PING motifs with corresponding activity and CFC/CFD maps, illustrating opposite directionality regimes.

Sociophysics Approach to Cultural and Economic Structure

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Extended abstract

We discuss how language can be used as a quantitative proxy for investigating large-scale social organization, employing methods from sociophysics and computational social science. Quite generally, we treat cultural identity as an emergent collective property arising from many individual interactions, making it suitable for analysis within a complex systems framework [1]. We operationalize cultural regions as geographically coherent patterns of shared discourse that can be analyzed from a lexical variation perspective. Then, using a large geotagged Twitter dataset from the United States, we extract regional topic patterns and apply smoothed principal component analysis followed by hierarchical clustering to identify dominant cultural units. Our results reveal robust large-scale structures, including a marked North–South division strongly influenced by African American culture, as well as East–West and noncontiguous urban–rural separations.

On the other hand, the socioeconomic background of people and how they use standard forms of language are not independent. However, the extent to which these correlations may be influenced by the mixing of people from different socioeconomic classes remains relatively unexplored. To this end, we investigate the interplay between socioeconomic status and the use of standard versus nonstandard English by means of geotagged Twitter data in roughly 7,000 administrative areas in England and Wales [2]. We quantify deviations from standard grammar and correlate these with high-resolution income data. Across eight metropolitan areas, we find a consistent pattern: as socioeconomic mixing increases, the correlation between income and frequency of nonstandard usage decreases. This effect is analyzed through mobility-based mixing matrices stratified by class (assortativity measures). Further, we introduce an agent-based model of linguistic variety adoption that incorporates both the status of a variety and speakers' intrinsic preferences. By analyzing the fixed points and their stability, we determine conditions under which standard and nonstandard forms dominate or coexist.

Overall, our work demonstrates how high-dimensional social media data can be used to uncover emergent macroscopic cultural and socioeconomic structures through standard multivariate, clustering and statistical methods. Our empirical and theoretical findings show that collective language patterns reveal the influence of geography, interaction and prestige in sociocultural differentiation.

Keywords: Complex systems; sociophysics; computational social science; computational sociolinguistics; language variation and change

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Power Grid Stability in Scenarios of Large Renewable Penetration

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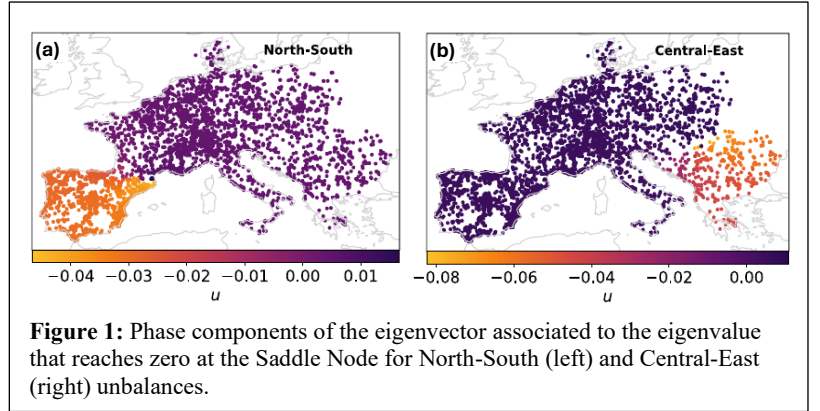
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Extended abstract

The power grid represents one of the largest and most complex artificial systems ever built, and its reliable operation is essential for modern societies and overall well-being. AC power grids operate as a very large synchronous system which practically lacks storage capacity, thus stable operation requires that at any time generation and demand are balanced. Since demand is continuously changing in time, traditionally the balance has been achieved by adapting generation to instantaneous demand. However, the urgent need to reduce CO₂ emissions requires the gradual phase-out of conventional plants based, increasing the amount of generation from renewable sources such as sun and wind which are subject to weather variability. On this respect we discuss here first a dynamical model that includes conventional and renewable generation, as well as demand variations that is capable of assimilating load and generation data [1]. The model can reproduce frequency fluctuations statistics with the current power mix, and it allows to simulate the frequency dynamics for different scenarios with a very high penetration of renewable energy. As a case study, we analyze the power grid of Gran Canaria Island. We characterize the frequency fluctuations and propose a method to estimate the control needed to keep frequency deviations within reasonable limits.

Second, renewables are also subject to geographical constraints, areas with high solar irradiation or persistent wind are often located far from major consumption centers. This spatial mismatch leads to significant long-distance power flows and increases stress on transmission networks. This is particularly relevant for large networks formed by the addition of smaller ones, such as the continental Europe synchronous area, which are not specifically designed for large inter-area flows. Here we discuss a general methodology for identifying critical lines in the long-distance transmission of power across large electric grids [2]. When the system is pushed to its operational limit, for instance by large power imbalances such as those generated by high penetration of variable renewable energy sources, the network gets destabilized and loses synchrony. As flows increase, we identify two different instability scenarios. In the first one, specific sets of lines reach their maximal load simultaneously, causing the grid to split into two desynchronized zones. In the second, more generic, instabilities occur well after one or several phase differences exceed $\pi/2$. Thus, line capacity limits are not the immediate cause of the instability, rather it emerges from grid topology constraints. The mechanism behind is a pair of complex eigenvalues, associated to a Jacobian eigenvector with nonzero components on nodes with generation, that become real (Belayakov-Devaney transition) and move apart, triggering a saddle-node bifurcation when one of them becomes zero. To push the system beyond this limit, we have proposed a mathematical trick converting certain lines to DC. The critical lines identified in this way match those that triggered the separation of the synchronous grid of continental Europe in two instances in 2021. We further discuss how the modes of the system provide information on which areas are more susceptible to lose synchrony with each other. In particular we find that, for a very broad range of scenarios, Pyrenees and Balkans are particularly vulnerable areas.



When the system is pushed to its operational limit, for instance by large power imbalances such as those generated by high penetration of variable renewable energy sources, the network gets destabilized and loses synchrony. As flows increase, we identify two different instability scenarios. In the first one, specific sets of lines reach their maximal load simultaneously, causing the grid to split into two desynchronized zones. In the second, more generic, instabilities occur well after one or several phase differences exceed $\pi/2$. Thus, line capacity limits are not the immediate cause of the instability, rather it emerges from grid topology constraints. The mechanism behind is a pair of complex eigenvalues, associated to a Jacobian eigenvector with nonzero components on nodes with generation, that become real (Belayakov-Devaney transition) and move apart, triggering a saddle-node bifurcation when one of them becomes zero. To push the system beyond this limit, we have proposed a mathematical trick converting certain lines to DC. The critical lines identified in this way match those that triggered the separation of the synchronous grid of continental Europe in two instances in 2021. We further discuss how the modes of the system provide information on which areas are more susceptible to lose synchrony with each other. In particular we find that, for a very broad range of scenarios, Pyrenees and Balkans are particularly vulnerable areas.

Keywords: Power grid dynamical modeling; Frequency fluctuations; Renewables variability; Grid stability; Inter-area flows;

Acknowledgments

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Excitable spatiotemporal dynamics and resilience in seagrass ecosystems

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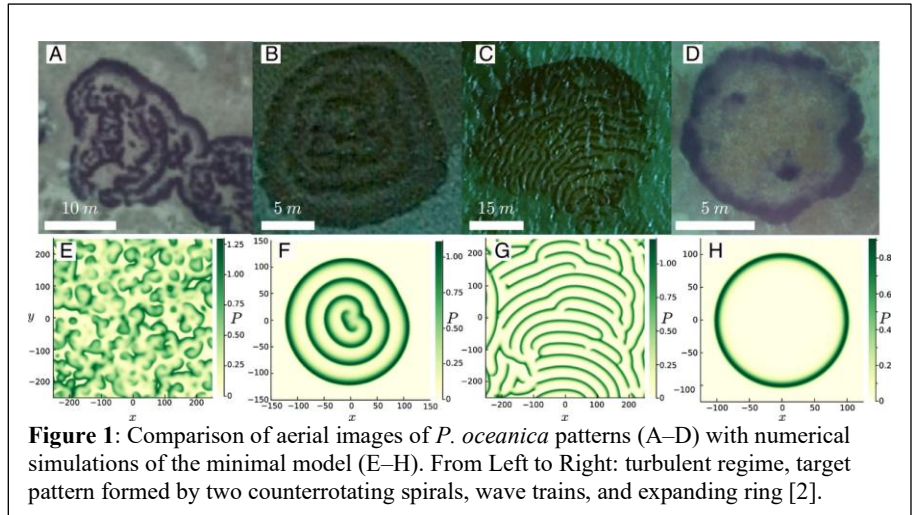
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Extended abstract

Spatial self-organization in ecosystems is increasingly understood as an emergent property of nonlinear interactions operating far from equilibrium. While most studies of ecological pattern formation have focused on stationary spatial structures, recent observations in seagrass meadows reveal intrinsically dynamical regimes characterized by propagating vegetation patterns [1,2]. Here we present a theoretical and empirical framework showing how spatiotemporal self-organization governs the resilience of Mediterranean *Posidonia oceanica* ecosystems.

Field observations and remote sensing reveal large-scale moving structures, including rings, arcs, and spiral-like fronts, propagating across seagrass landscapes over ecological timescales. These dynamics arise from the coupling between plant growth and sediment biogeochemistry, particularly the accumulation and diffusion of toxic hydrogen sulfide produced under anoxic conditions. We show that the interaction between vegetation and toxicity drives the ecosystem into an excitable regime, in which localized perturbations trigger self-organized traveling pulses [1].



A minimal reaction–diffusion model capturing vegetation growth, clonal expansion, and sulfide dynamics reproduces the observed propagating patterns and predicts characteristic properties of excitable media, including pulse velocity, stable propagation, and interaction-induced annihilation (Figure 1). The agreement between theoretical predictions and field observations supports the interpretation of seagrass meadows as large-scale natural realizations of excitable systems previously studied primarily in chemical and physical contexts [1].

Beyond pattern formation itself, the analysis reveals a functional role of spatiotemporal dynamics in ecosystem stability. Traveling pulses continuously redistribute biomass and toxic compounds in space, preventing sustained local stress accumulation. As a result, patterned dynamical states allow ecosystem persistence under environmental conditions that would otherwise lead to uniform meadow collapse. Spatiotemporal self-organization therefore acts as an emergent resilience mechanism rather than merely a precursor of degradation [2].

This framework links ecological resilience to dynamical systems concepts such as excitability and nonlinear wave propagation. Seagrass ecosystems thus provide a natural laboratory in which excitable dynamics operate at landscape scales, illustrating how nonlinear spatial processes can regulate ecosystem responses to environmental stress. These results highlight the importance of incorporating spatiotemporal dynamics into theories of critical transitions and offer new avenues for interpreting remote-sensing observations and assessing ecosystem vulnerability under global change.

Keywords: Excitable media; Spatiotemporal Pattern Formation; Ecosystem Resilience; Reaction-diffusion dynamics; Travelling Pulses.

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Application of Artificial Intelligence in Pharmaceutical Quality Control

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Extended abstract

The pharmaceutical industry is responsible for ensuring the quality, safety, and efficacy of medicinal products through rigorous quality control (QC) testing ¹. As regulatory requirements become increasingly strict and the complexity of pharmaceutical formulations grows, traditional QC methods face challenges related to efficiency, data handling, and reproducibility. Conventional analytical testing, while reliable, it is laborious, and requires manual effort, and expertise. These limitations have encouraged the adoption of advanced technologies, such as Artificial Intelligence (AI) to improve QC processes.

AI has shown significant potential in enhancing a wide range of pharmaceutical quality control tests, including dissolution testing, content uniformity and assay determination. Among these, dissolution testing plays a critical role in evaluating the rate and extent of drug release from solid dosage forms, directly impacting bioavailability and therapeutic performance ². The process of deciphering the dissolution profiles can be complex, particularly when comparing multiple formulations or detecting subtle variations between batches. AI-based models can process dissolution data more efficiently, identifying trends, predicting release behavior, and enabling faster and more accurate interpretation of results.

A key advantage of AI in pharmaceutical QC lies in its ability to handle complex, high-dimensional datasets and provide real-time insights. This is particularly valuable in modern laboratories, where large volumes of data are generated daily from multiple analytical techniques. AI systems can enhance data integrity, streamline workflows, and support compliance with regulatory requirements, such as Good Manufacturing Practice (GMP) ³.

Despite these advantages, several challenges remain in the implementation of AI in the QC processes. The performance of AI models depends heavily on the availability of high-quality, well-structured data ⁴. Additionally, regulatory concerns regarding model validation, transparency, and reliability must be addressed to ensure acceptance by authorities. Integration with existing laboratory systems and the need for specialized expertise also represent potential barriers.

In conclusion, AI has the potential to significantly improve pharmaceutical quality control testing by enhancing the accuracy, efficiency, and interpretation of analytical methods, such as dissolution, assay, and impurity analysis. As technology continues to ripen and regulatory frameworks adapt, AI is expected to play an increasingly important role in ensuring the consistent quality of pharmaceutical products and safeguarding patients' health.

Keywords: Artificial Intelligence; Quality control; Pharmaceutical companies; Formulation development.

Acknowledgments

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Nanoparticle Drug Delivery through AI and High-Throughput Screening in Formulation Design and Biological Performance

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Extended abstract

Nanoparticle drug delivery systems have emerged as promising platforms for improving the therapeutic performance of small molecules, biological macromolecules, and nucleic acid cargos by modulating solubility, stability, biodistribution, cellular uptake, and release kinetics. Despite significant advances in nanomedicine, the translation of nanoparticle formulations into predictable biological performance remains a major challenge. This is mainly due to the fact that nanoparticle behavior is determined by the combined influence of formulation composition, preparation parameters, physicochemical characteristics, and biological interactions. Parameters such as biomaterial type, lipid or polymer ratio, particle size, polydispersity index, surface charge, morphology, encapsulation efficiency, and colloidal stability are closely interrelated, and even small variations may lead to substantial differences in therapeutic outcome ¹.

A major challenge in nanoparticle drug delivery is the limited ability to directly correlate formulation design with biological response. Nanoparticles that appear optimal on the basis of physicochemical characterization do not always exhibit the expected performance under biological conditions. Following administration, they encounter a dynamic environment in which biomolecular adsorption, protein corona formation, immune recognition, tissue-specific barriers, intracellular trafficking, and endosomal entrapment can significantly alter their fate ². As a result, drug delivery is not governed exclusively by the initial formulation properties, but also by the interaction of the nanosystem with the biological environment. This highlights the need for development strategies capable of addressing the multidimensional nature of nanoparticle behavior from formulation design to therapeutic action.

In this context, computational tools, data-driven approaches, and artificial intelligence (AI) are increasingly being used to support the development of nanoparticle drug delivery systems. These methods enable the analysis of complex datasets, the identification of relationships amongst formulation variables, and the prediction of properties associated with improved biological performance ³. Their value is further enhanced when combined with high-throughput screening approaches, including automated formulation methods, microfluidic technologies, rapid physicochemical characterization, and biological evaluation. These strategies enable the systematic exploration of formulation design and facilitate the identification of nanoparticle systems with optimized properties for specific therapeutic applications. However, important limitations remain, including variability in experimental design, insufficient standardization of reported parameters, limited model generalizability, and the persistent difficulty of translating *in vitro* findings into reliable *in vivo* outcomes. These limitations indicate that progress in nanoparticle drug delivery depends not only on the development of more advanced nanocarriers, but also on a deeper understanding of the relationships connecting formulation parameters, biomaterial properties, and biological performance. Within the context of chaos and complexity, nanoparticle drug delivery represents a field in which multiple interacting variables influence physicochemical and biological behavior, thus determining the therapeutic outcome. A more integrated understanding of these interactions is essential for the rational design of nanosystems with improved efficacy and translational potential.

Keywords: nanoparticle drug delivery; complexity; artificial intelligence; formulation design

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Shaping Galactic Peanuts: Orbital Stability and the Role of Central Mass Concentrations

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Extended abstract

Boxy/peanut (b/p) bulges and the associated X-shaped structures observed in edge-on barred galaxies are widely interpreted as manifestations of the three-dimensional orbital structure of stellar bars. Previous work has demonstrated that these features arise from the collective behavior of families of periodic orbits that bifurcate from the main bar-supporting backbone at vertical resonances. The ability of these families to trap surrounding stellar material and sustain coherent orbital flows depends critically on their stability properties and on the global organization of phase space in rotating barred potentials.

In this contribution, we review the principal dynamical mechanisms that shape the inner regions of galactic bars and lead to the formation of b/p bulges. Particular emphasis is placed on the role of vertically extended orbit families associated with the “x1-tree” and on how transitions between stability and various types of instability influence the spatial distribution of stars and the resulting morphology of the bar in side-on projections. We discuss how the extent of stable domains along the characteristic curves of these families determines the efficiency with which they can support peanut-shaped and X-shaped structures, as well as how nearby quasi-periodic and chaotic orbits contribute to the overall density enhancement in the central regions.

In addition, recent results will be presented concerning the influence of a classical spheroidal bulge embedded in the central region of a bar on the stability properties of the principal families of periodic orbits. Changes in the central mass concentration can alter the location of vertical resonances, modify the stability intervals of the relevant families, and consequently affect both the strength and the detailed morphology of the resulting peanut and X-shaped structures. These findings provide further insight into the dynamical coupling between the internal mass distribution of barred galaxies and the observable characteristics of their central structures.

Overall, the presented framework highlights the importance of orbital stability analysis as a diagnostic tool for understanding the diversity of boxy/peanut morphologies and for linking the observed structure of barred galaxies with the underlying dynamical mechanisms governing their evolution.

An Internet of Things Chaos Demonstrator

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Extended abstract

An IoT chaos demonstrator is a low-cost embedded system designed to digitally implement and visualize the chaotic dynamics of nonlinear systems using microcontroller platforms, such as Arduino. This system bridges theoretical chaos models with practical digital realization, facilitating real-time demonstrations of chaotic behavior through graphical outputs on an integrated display. It employs numerical methods, including Euler integration and fixed-point arithmetic, to simulate both discrete chaotic maps and continuous-time chaotic flows within the computational constraints of IoT devices [1]. This demonstrator serves as an effective educational and experimental tool, illustrating key features of chaos theory, such as sensitive dependence on initial conditions, bifurcations, time-series, and strange attractors [2], while highlighting the challenges and solutions of embedding complex nonlinear dynamics into resource-limited IoT hardware devices.

The operation of the chaos demonstration system is organized as a structured interaction flow that separates system selection from visualization functionality. Initially, the user selects the type of chaotic system, distinguishing between discrete maps and continuous-time models. Subsequently, the user defines the mode of observation, such as temporal evolution, bifurcation behavior, or phase space representation, depending on the selected system. Once these parameters are defined, the system dynamically generates and visualizes the corresponding chaotic behaviour in real time. This interaction model allows seamless transitions between different systems and visualization modes, supporting exploratory analysis and enhancing the interpretability of nonlinear dynamics. The overall design emphasizes clarity, flexibility, and ease of use, consistent with embedded system implementations for real-time chaotic simulation [1].

The introduction of nonlinear dynamics at school level is still an open issue, it appears in extracurricular activities, though; other works introducing “exotic” nonlinear dynamics topics, such as memristors, have been proposed [3]. The purpose of the low-cost chaos demonstrator is to offer an accessible and practical platform for the real-time visualization and study of chaotic systems in engineering education, even science education at school. By utilizing affordable hardware components and simple yet effective visualization techniques, such as plotting computed points on a TFT display at consistent time intervals, the demonstrator ensures a smooth and responsive representation of chaotic dynamics. This approach enables users to observe complex chaotic behaviours interactively, facilitating both experimental investigations and educational demonstrations of chaos theory [2]. Its low cost and straightforward design make it an ideal tool for academic environments, research settings, and enthusiasts who may lack access to expensive or sophisticated laboratory equipment.

Ultimately, the demonstrator bridges the gap between theoretical chaos concepts and tangible, observable phenomena, thereby enhancing the understanding and engagement with nonlinear dynamical systems [3]. Unlike most existing studies that focus on simplified, single-system educational implementations with basic LED-based visualizations [1,2], [4], the proposed demonstrator provides an integrated platform combining theoretical modelling, numerical simulation, and microcontroller-based implementation. It supports multiple discrete and continuous chaotic systems and enables real-time advanced visualization, offering a more comprehensive and scientifically robust tool for the study and education of nonlinear dynamical systems. Future work could focus on enhancing the dynamic parameter variation for studying chaotic phenomena, as well as design a teaching guide utilizing the demonstrator (for instance for school lab use).

Keywords: Chaos theory, nonlinear dynamics, bifurcation analysis, IoT systems, Arduino, embedded computation, real-time visualization

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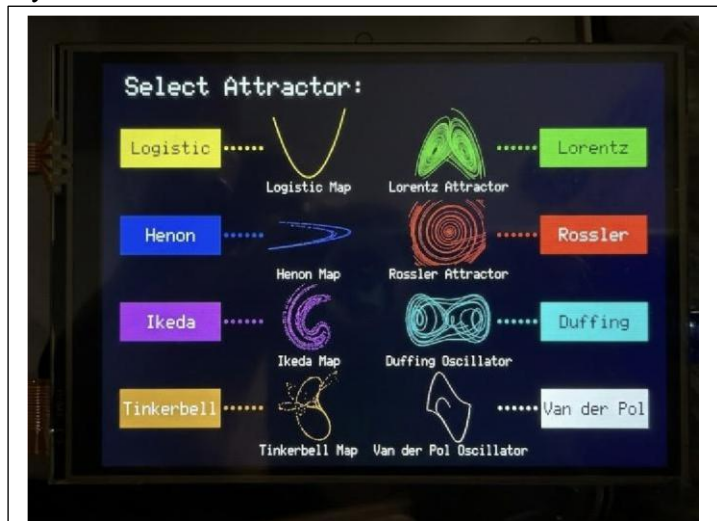


Figure 1: User interface of the proposed IoT chaos demonstrator showing multiple chaotic systems and real-time visualization previews.

Multi-Task Convolutional Approach for Structural Characterization of Complex Moiré Lattices

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Extended abstract

Moiré patterns, formed by the superposition of periodic structures, exhibit complex, large-scale interference effects that are critical to the design of advanced two-dimensional materials [1]. Applications of such patterned materials include superconductive properties [2] and membranes [3]. Designing these materials for specific functionalities requires navigating a vast and nonlinear parameter space, which leads to severe computational bottlenecks when scaling.

This study introduces a high-performance, multi-task deep learning framework engineered for the data-driven inverse design of Moiré lattices. To capture the complex spatial hierarchies of these structures, we developed a parallelized computational pipeline, generating a dataset of 20,000 simulated Moiré interference patterns. The structural data is then processed through a Convolutional Neural Network (CNN) featuring Batch Normalization and Global Average Pooling. Accelerated via mixed-precision training and XLA compilation, the model's shared feature-extraction backbone bifurcates into two distinct predictive heads:

1) Structural Complexity Classification: A classification head that accurately identifies the number of superimposed structural layers driving the nonlinear pattern.

2) Mesh Parameter Regression: A linear regression head optimized with heavily weighted mean squared error (MSE) to predict the continuous mesh width.

Simultaneously evaluating classification accuracy and regression metrics (R^2 and Mean Absolute Error), our results demonstrate that this CNN architecture can capture the intricate interdependencies between lattice layers and geometries. Ultimately, this approach provides a scalable framework, with a goal toward tunable material configurations.

Keywords: Multi-Task Learning, Complex Materials, Convolutional Neural Networks, Moiré Patterns, Inverse Design

Acknowledgments

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Disturbance Amplification in Production Systems: A Nonlinear Approach

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Extended abstract

Production systems are generally structured around predefined workflows and expected operating conditions. However, in practical settings, even limited operational disturbances may influence the broader production process in ways that are not fully predictable. A short delay in material supply, a temporary machine interruption, or a minor change in task sequence may affect multiple stages of production and create outcomes that extend beyond the initial point of disruption.

This becomes particularly relevant when production systems are considered as interconnected operational environments in which multiple variables interact continuously. A local disturbance may gradually influence coordination, timing, and resource allocation in other parts of the system. In this respect, production systems may exhibit characteristics associated with nonlinear dynamics, particularly when small initial changes produce broader system-level effects.

Previous studies suggest that nonlinear interactions may produce disproportionately complex outcomes even when initial changes are small. May (1976) demonstrated that simple mathematical models can generate highly complex dynamic behavior, while Strogatz (2015) highlighted the importance of feedback, instability, and sensitivity to initial conditions in complex systems. In manufacturing contexts, Papakostas et al. (2009) showed that increasing structural complexity in production environments can be examined using nonlinear dynamics approaches. Together, these studies provide a theoretical basis for interpreting production systems as structures in which minor operational disturbances may lead to amplified and potentially unstable effects.

Building on existing studies of nonlinear behavior in complex systems, this study proposes a simple nonlinear conceptual model to explain how minor operational disturbances may propagate and amplify across interconnected production stages. The proposed formulation is conceptually inspired by the classical logistic map, which is widely used in chaos theory to represent nonlinear feedback dynamics, and is extended here by incorporating an external disturbance term to reflect operational disruptions in production systems.

To provide a structured interpretation of disturbance propagation, a simple nonlinear model is proposed:

$$x_{t+1} = x_t + \alpha x_t (1 - x_t) - \beta d_t$$

In this formulation, x_t represents the operational state of the production system at time t , while d_t denotes the magnitude of an external disturbance. The parameter α captures the internal feedback intensity of the system, reflecting how strongly current conditions influence future states. The parameter β represents the system's sensitivity to external disturbances.

The nonlinear term $\alpha x_t (1 - x_t)$ introduces feedback-driven dynamics, allowing the system to exhibit amplification effects under certain conditions. Even small disturbances (low d_t values) may lead to disproportionately large deviations in system behavior when feedback intensity is sufficiently high. This structure reflects a key principle of chaos theory: sensitivity to initial conditions, where minor changes can lead to significantly different system trajectories over time.

By integrating this nonlinear perspective, the study demonstrates that production systems may not only respond proportionally to disturbances, but may also exhibit amplification and instability patterns under specific conditions. This supports the interpretation of production environments as complex adaptive systems with potential chaotic behavior.

Keywords: Chaos theory; Nonlinear dynamics; Complex systems; Production systems; Operational disturbances

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Influence Maximization under the Continuous-Time SIR-Voter Model

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Extended abstract

In real-world social networks, individuals often express their opinions only when they are actively engaged or "infected" by a specific topic [1],[2]. To capture this behavior, recent work has introduced the SIR-Voter model, a coupled dynamics framework that extends the fundamental Voter model [3] by integrating it with an underlying epidemic process (SIR). In this model, the classic Voter dynamics are modified so that node activity is governed by the epidemic process, and only infected nodes express their opinion. Thus, when a node is selected to update its state, it adopts the opinion of a randomly selected infected neighbor.

While the dynamics of the SIR-Voter model have been explored, the Influence Maximization Problem (IMP) [4] within this framework remains an open challenge. Crucially, while existing IMP literature on coupled opinion and activation dynamics has predominantly focused on discrete-time environments [5], the study of IMP under strictly continuous-time dynamics—where an activation model dynamically dictates opinion expression—remains a largely unexplored frontier. The complexity of this problem arises because opinion spreading is strictly constrained by the continuous-time epidemic layer. Since a node can only spread its opinion while it is actively "infected", maximizing the spread of an opinion requires a seed selection strategy that considers both the structural connections of the network and the underlying coupled activation-opinion dynamics.

In this work, we address this gap by proposing a Greedy node selection algorithm, specifically designed to solve the IMP under the unique continuous-time constraints of the SIR-Voter model. The influence spread objective function is defined as the net cumulative expressed opinion of all nodes over the entire duration of the spreading process. We compare our proposed selection algorithm against baseline IM strategies within this framework. We perform our experiments on a synthetic Barabási–Albert (BA) network and two real social networks: Wiki-Vote and Facebook. Simulation results indicate that our proposed algorithm outperforms all other baseline strategies in terms of influence spread across every tested scenario.

Finally, an outlook for our work is to design a node selection algorithm to solve the Targeted Influence Maximization Problem under the SIR-Voter model.

Keywords: Influence Maximization; Continuous-Time; SIR model; Voter Model; Opinion Dynamics

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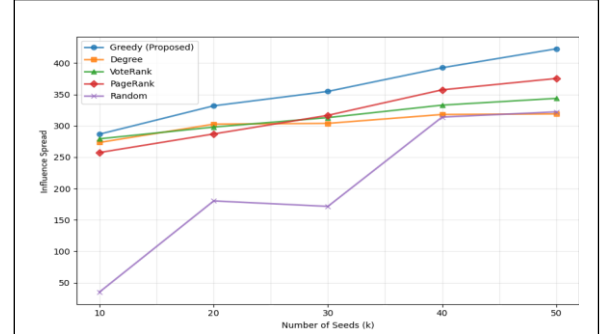


Figure 1: Comparing the influence spread as calculated for the proposed Greedy selection algorithm (in blue) against the other four baseline strategies (Degree in orange, VoteRank in green, PageRank in red, and Random in purple) across varying initial seed set sizes ($k = 10, 20, 30, 40, 50$) on the Facebook network.

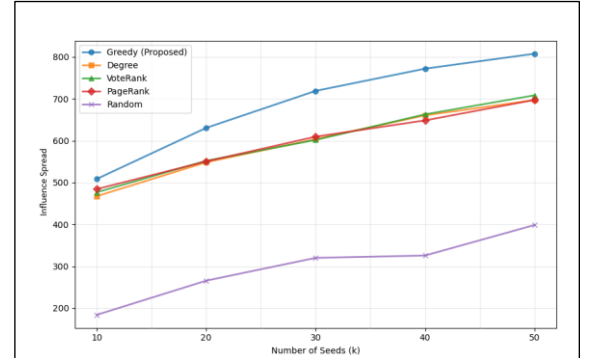


Figure 2: Comparing the influence spread as calculated for the proposed Greedy selection algorithm (in blue) against the other four baseline strategies (Degree in orange, VoteRank in green, PageRank in red, and Random in purple) across varying initial seed set sizes ($k = 10, 20, 30, 40, 50$) on the Barabási–Albert (BA) network.

Multiscale Shannon Entropy of Experimental SEM Textures

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Extended abstract

Shannon entropy provides a general measure of uncertainty that links information theory with the statistical description of disordered media [1,2]. In image analysis, the entropy of the raw pixel-intensity histogram is often used as a compact descriptor of texture. However, this global measure collapses all spatial scales into a single distribution: images with similar intensity statistics but different spatial organisation can therefore be assigned almost identical entropy values.

Multiscale entropy overcomes this limitation by evaluating how local intensity statistics change as the observation scale increases. Previous work showed that the resulting entropy curves can quantify rough-surface complexity and that their amplitude depends critically on the binning of the intensity histogram [3]. Building on that framework, we analyse experimental SEM textures through a multiscale entropy curve $E(r)$. For each radius r , every pixel is replaced by the mean of nine samples from a symmetric stencil, consisting of the centre pixel, four axial neighbours and four diagonal neighbours, and the Shannon entropy of the histogram of these local averages is then computed.

This procedure converts each micrograph into a scale-dependent signature that reflects how disorder, contrast and characteristic structural length scales are mixed by progressively larger neighbourhoods. We apply the analysis to a broad set of SEM images representing different types of nanostructured and microstructured surfaces. The resulting $E(r)$ curves show distinct behaviours across texture families: some remain low and nearly flat, others display oscillations associated with periodic order, while more heterogeneous samples exhibit non-monotonic responses.

These trends indicate that multiscale Shannon entropy captures information that is inaccessible to single-scale histogram descriptors. The $E(r)$ curve therefore offers a compact and physically interpretable basis for comparing SEM textures, supporting classification tasks, and guiding the inverse design of complex materials with targeted structural characteristics.

Keywords: Shannon Entropy, Multiscale Analysis, SEM Image Texture, Complex Surfaces, Nanostructures

Acknowledgments

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A Data Driven Approach to Projecting Boreal GPP from Complex Climate Drivers

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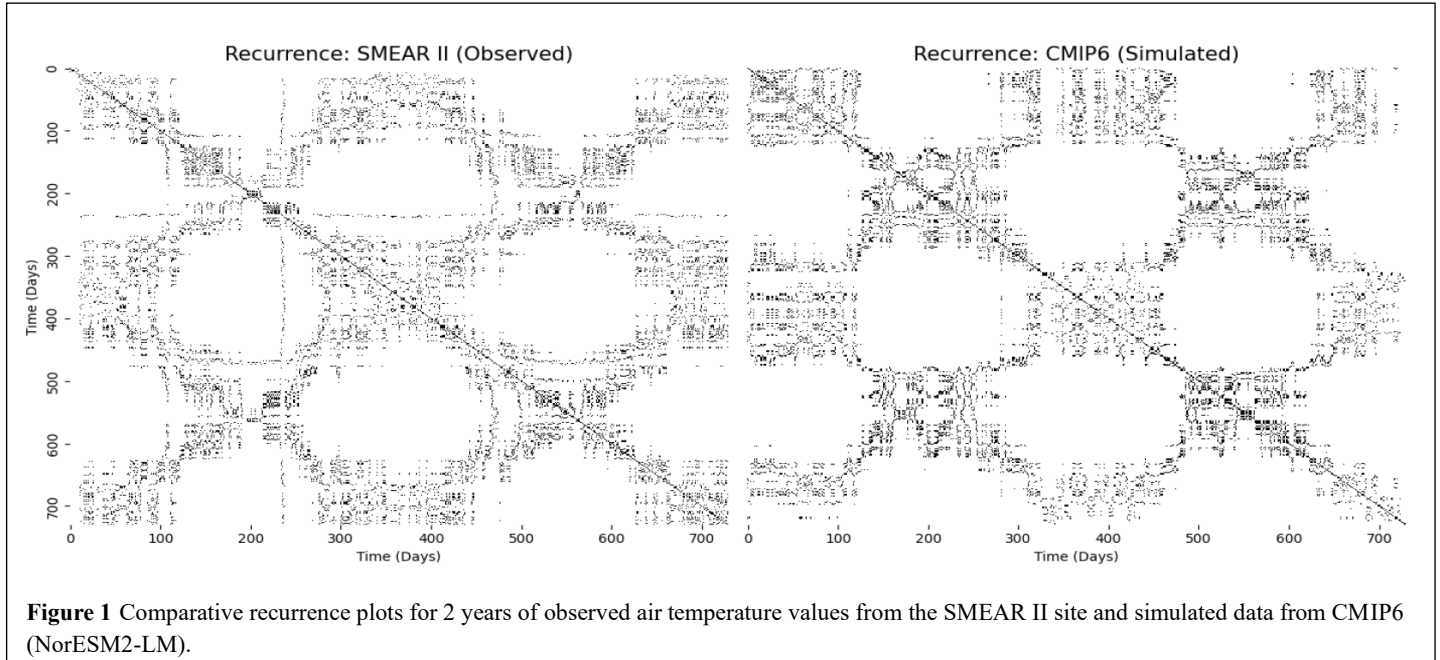


Figure 1 Comparative recurrence plots for 2 years of observed air temperature values from the SMEAR II site and simulated data from CMIP6 (NorESM2-LM).

Modelling forest productivity under environmental variability remains a central challenge in terrestrial ecology, particularly under changing climate conditions. Here, we combine data-driven modelling with nonlinear time series analysis to investigate the dynamical structure of environmental drivers and of gross primary productivity (GPP) in a boreal forest system. Using fifteen years (2003–2018) of daily observations from the SMEAR II station in Hyytiälä, Finland[1], we model GPP as a function of photosynthetically active radiation (PAR), atmospheric CO₂, air temperature, and relative humidity using linear regression, eXtreme Gradient Boosting (XGBoost), and deep neural networks (DNNs), with evaluation on an independent five-year period (2018–2022). All models demonstrate strong predictive skill ($R^2 = 0.79\text{--}0.90$), with the DNN performing best. To assess whether climate model outputs capture comparable dynamical structure, we analyse CMIP6 historical simulations of surface radiation, temperature, and humidity using information-theoretic and recurrence based complexity measures. We find that these variables exhibit complexity values comparable to in situ observations at SMEAR II, suggesting that, at the level of observable time series, CMIP6 models reproduce the effective dynamical variability of key environmental drivers.

Finally, we use the trained models to project GPP under multiple CMIP6 climate scenarios, finding an overall increase in productivity (mean ~47%), with diminishing gains under more extreme forcing. Taken together, these results indicate that both the predictive relationships and the underlying variability structure of environmental drivers are captured sufficiently well to support data-driven projections of ecosystem response, while also motivating further investigation into the origins of observed complexity in climate–biosphere interactions.

Keywords: forest models; climate models; complexity; entropy; recurrence plot.

Acknowledgments

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Nonlinear Coupling Effects in Two Cell Discrete Time Neural Maps

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Extended abstract

Spiking neural networks (SNNs) have demonstrated remarkable effectiveness in several practical applications, such as nonlinear control systems [1], event-based vision processing [2], autonomous and bio-inspired robotics [3]. However, the widespread adoption of classical continuous-time models is limited by high computational complexity and the resulting implementation costs. To overcome this challenge, this work focuses on the use of discrete-time neural maps. This kind of map enables the faithful replication of complex neural dynamics with a drastically reduced computational burden.

Specifically, we analyze the effects of nonlinear coupling between two discrete-time neurons [4], with particular attention to the ability of such coupling to determine and modulate the dynamic behavior of the entire system. The primary goal of the research is to characterize the onset of induced firing patterns in normally quiescent neurons that, in the absence of external stimulation or coupling, exhibit no spontaneous activity [5]

The core of the analysis lies in the study of how a quiescent cell responds and adapts when stimulated by a firing cell that exhibits a variety of distinct dynamic behaviors. This paper explores how the quiescent cell modifies its firing pattern as a function of the nature of the signal produced by the firing cell, which can be periodic, quasi periodic, or chaotic [6]. In this way, it highlights how the behavioral richness of the source is reflected and translated into equally varied response patterns in the quiescent cell.

The characterization of the different emerging spiking regimes is conducted through numerical simulations and a detailed stability analysis, focusing on a single parameter that modulates the strength of the nonlinear coupling. As this parameter varies, a transition through a wide range of dynamical behaviors is observed, from regular and periodic spiking, through bursting and multistable regimes, to fully chaotic dynamics [7]. The results obtained suggest that the nonlinear coupling mechanism is a key element in generating and controlling dynamic complexity in discrete-time neural networks.

Keywords: Nonlinear Dynamics, Spiking Neurons, Chaos, Synchronization

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Complex Behaviour and Chaos in Nanostructured Lipid Carriers

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Extended abstract

Nanostructured lipid carriers (NLC) are widely used for the encapsulation and delivery of lipophilic active compounds. However, their physicochemical characterization is typically based on static descriptors that may not adequately capture their dynamic structural evolution [1]. The formation of lipid nanosystems is governed by self-assembly processes, whereby amphiphilic and lipid molecules organize into ordered nanostructures through non-covalent interactions. This mechanism supports the structural organization of NLC and is intrinsically linked to their time-dependent evolution, internal rearrangements, and colloidal stability. According to recent studies [2], the dynamical evolution and complexity of lipid-based systems suitable for drug encapsulation can be monitored through time-resolved measurements of their physicochemical properties, such as the mean particle radius. In the present work, the temporal evolution of a NLC system (Table 1) was monitored through dynamic light scattering (DLS), assessing mean particle size, polydispersity index (PdI), and ζ -potential, and its behavior at a representative stage (day 4) was analyzed. The observed dynamics were investigated using established tools from nonlinear time series analysis in order to characterize the nature of the system's complexity.

The calculated Lyapunov exponent ($\lambda=0.114$) indicates sensitivity to initial conditions and provides clear evidence of deterministic chaotic behavior. In parallel, the estimated fractal dimension ($v=2.63$) suggests a low-dimensional yet complex underlying structure. As seen in Figure 1, phase space reconstruction further revealed a minimum embedding dimension of $m=3$, while the global dynamics of the system appear to extend up to five effective degrees of freedom.

These findings support the interpretation of the NLC as a self-organizing dynamical system [3] governed by deterministic nonlinear interactions rather than purely stochastic processes. The presence of low-dimensional chaos implies that, despite the apparent complexity, the system's behavior is controlled by a limited number of variables, which may be linked to key formulation and processing parameters.

To conclude, this work introduces a nonlinear dynamics perspective to the study of lipid-based nanocarriers, providing new insights into their time-dependent behavior, structural evolution, and potential variability. Such an approach may contribute to improved understanding and control of formulation performance, particularly in relation to stability and drug delivery properties.

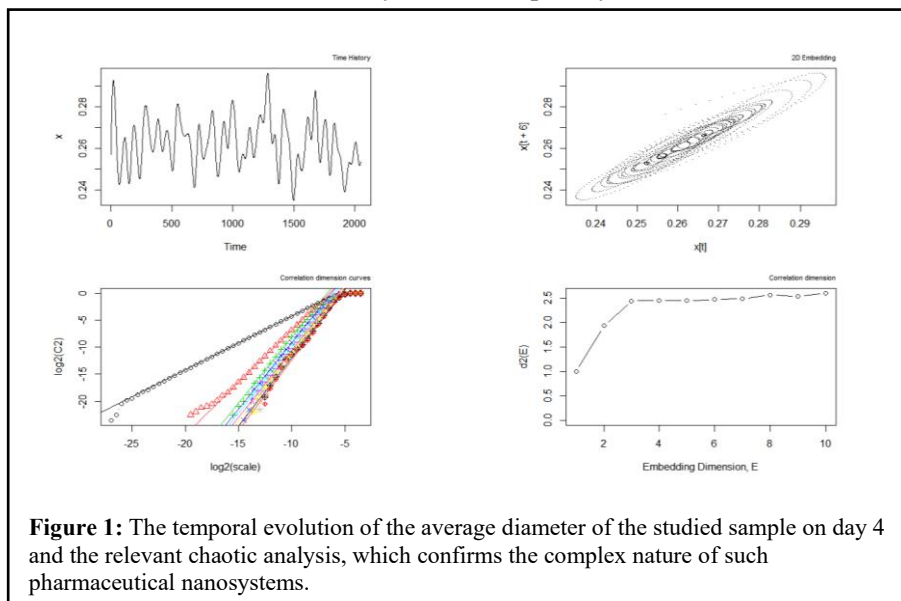
Keywords: Nanostructured lipid carriers, Colloidal stability, complexity, chaotic behavior.

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Table 1: The composition of the prepared Nanostructured lipid carriers (NLCs)

Ingredient	Function	% w/w
Caprylic/capric triglyceride	Liquid lipid	1
Hydrogenated palm oil	Solid lipid	2
Soy-Lecithin	Emulsifier	2.5
PEG-15-Hydroxystearate	co-Emulsifier	1
Propylene Glycol Caprylate	Preservative	3
Water	Aqueous phase	90.5



Refuting Causal Relations for Synchronized Pathogen Dynamics

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Extended abstract

Identifying causal relations is a critical challenge in the study of real-world chaotic dynamical systems, particularly for studying the spread of pathogens in host populations. Whether dealing with measles in humans, foot and mouth disease in livestock, or white-nose syndrome in bats—understanding causal relations is essential for understanding the underlying factors driving growth, decline and re-emergence of pathogen dynamics. This knowledge is vital for informing policy and management strategies aimed at controlling the spread of pathogens.

Unfortunately, existing tools designed to identify causal directions from disease incidence data, especially in synchronized systems, often suffer from high false detection rates [1,2].

To address this challenge, we propose Bootstrap Comparison of Attractor Dimensions (BCAD), a novel method that focuses on refuting false causal relations using a criterion based on the correlation dimension [3] and other techniques for estimating intrinsic dimensions. We test the performance of BCAD, demonstrating its efficacy in correctly refuting false causal relations on two datasets: a model system that consists of two strains of a pathogen driven by a common environmental factor, and a real-world pneumonia and influenza incidence time series from the United States. We compare BCAD to Convergent Cross Mapping (CCM)[4], a prominent method of causal detection in nonlinear systems. In both datasets, BCAD correctly refutes the vast majority of spurious causal relations which CCM falsely detects as causal. The utility of BCAD is emphasized by the fact that our models and data displayed synchrony, a situation known to challenge other causal detection methods.

In conclusion, we demonstrate that BCAD is a useful tool for refuting false causal relations in nonlinear dynamical systems arising in the study of the spread of pathogens. BCAD offers an approach for discerning true causal relations from false ones and may also find applicability beyond the study of pathogens and their spread in host populations.

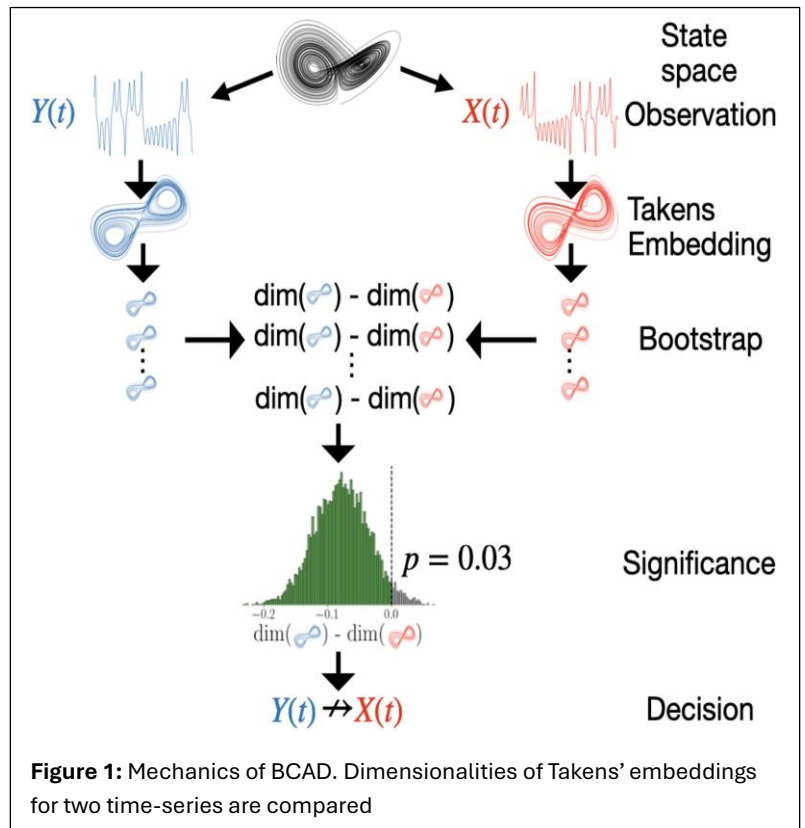
Keywords: Causal inference; time-series; epidemiology.

Acknowledgments

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Chaos, Fractals, and Ergodicity in Nonlinear Quantum Protocols

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Extended abstract

Measurement-induced postselection provides a simple and physically accessible route through which elementary quantum circuits can generate genuinely nonlinear evolution on quantum states. While the linearity of quantum mechanics usually prevents the emergence of classical-like chaos, postselection breaks the deterministic and unitary nature of the system and turns the time evolution of the surviving subsystem into a probabilistic and effectively nonlinear process. When such transformations are applied iteratively, with the output of one successful step serving as the input of the next, they naturally define a discrete-time dynamical system on the quantum state space. Even simple protocols built from multi-qubit entangling gates, projective measurements, postselection, and a single parameterized one-qubit unitary already give rise to a remarkably rich class of nonlinear dynamics, including stable and unstable fixed points, competing attractors, fractal basin boundaries, and exponential sensitivity to initial conditions. This establishes iterated nonlinear quantum protocols as a natural bridge between quantum information processing and nonlinear dynamical systems, providing both a physically motivated setting for studying complex dynamical phenomena in quantum systems and a flexible framework for applications in quantum state manipulation, distillation, and validation.

This connection between iterated quantum protocols and nonlinear dynamics has led to the identification of several characteristic phenomena. Earlier work showed that measurement-induced nonlinear transformations can be used for quantum state matching and state-discrimination-like tasks [1]. Later studies revealed distinct nonlinear features including competing attractors, fractal basin boundaries, and strong sensitivity to initial conditions. For mixed initial states, noisy inputs were shown to induce a purity-driven transition: above a critical purity, the dynamics retains a Julia set-like boundary structure separating asymptotic outcomes, while below it the fractal structure disappears and the dynamics becomes globally regular [2,3]. Some of these characteristics of the nonlinear protocols were later demonstrated experimentally in a photonic implementation [4]. More recent work showed that the chaotic dynamics remains robust under realistic imperfections, with moderate preparation noise and coherent gate errors deforming but not destroying the underlying fractal structure [5]. Related nonlinear constructions have also enabled universal and unambiguous concentration and distillation of Bell pairs [6]. Together, these results establish iterated nonlinear quantum protocols as both useful quantum-information primitives and possible experimental realizations of complex nonlinear dynamics. Recently, we have further expanded this picture by identifying a class of iterated nonlinear quantum protocols that exhibit globally chaotic, strongly mixing, and ergodic-like dynamics [7]. For a particular choice of the final single-qubit unitary, the pure-state dynamics explores the entire Bloch sphere, providing a physical realization of ergodic behavior in a nonlinear quantum map. For mixed initial states, representing imperfect state preparation, the protocols retain key signatures of the ergodic behavior observed for pure states. To quantify the robustness of this behavior against such noise, we introduce quasi-ergodicity: ensembles initialized at fixed purity rapidly spread over all directions before radial contraction drives them toward the maximally mixed state.

Acknowledgments

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Chaos suppression due to a hysteretic effect

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Extended abstract

In recent decades, the scientific community has shown growing interest in the study of chaotic circuits and their practical applications. Researchers have focused on the design of nonlinear (chaotic) electronic oscillators and their integration into engineering fields such as cryptography and telecommunications. A representative example of a chaotic cryptosystem is the non-autonomous chaotic, electronic oscillator examined in the present study. The class of circuits/systems, like the one studied hereby, allows for systematic investigation of chaotic dynamics through controlled modifications of its electronic structure, enabling deeper insight into its underlying behavior. The proposed topology, studied in [1], is based on an analog periodic oscillator bearing a nonlinear feedback loop subjected to external excitation. The emerging topology is capable of exhibiting not simply chaotic behavior, but also rich chaotic dynamics and experimental verification of various chaotic phenomena. This configuration, illustrated in Figure 1, has been extensively studied both theoretically and experimentally [2]. One of its principal applications lies in chaotic synchronized communication for encrypted data transmission [3]. A key question arises: to what extent do modifications in the nonlinear feedback path may influence the system's chaotic behavior? What changes occur if the conventional comparator, that is included in the feedback path, is replaced by a comparator with hysteresis (Schmitt trigger), as shown in Figure 2? Would the system continue to exhibit the same rich dynamics chaotic dynamics, and if so, over which frequency ranges?

Exploring exactly this option, the work presented studies the topology of a non-autonomous chaotic oscillator in which the nonlinear feedback element is implemented using a Schmitt trigger instead of a standard comparator (Figure 2). The defining characteristic of this component is hysteresis, which introduces two distinct voltage thresholds that govern the switching behavior of the output. This feature enhances the circuit's robustness by suppressing not only the influence of external noise, but also the diverging properties of its dynamics by preventing small input fluctuations from inducing unintended transitions. As a result, the output signal is free from spurious artifacts, ensuring the reliability of the observed behavior. Consequently, any detected chaotic dynamics can be attributed to the intrinsic properties of the system and its sensitivity to initial conditions, rather than to external disturbances.

The incorporation of hysteresis into the nonlinear feedback significantly enhances the circuit's functional characteristics, making it particularly suitable for specialized applications. In this configuration, chaotic behavior arises purely from the system's internal nonlinearity and dynamic feedback mechanisms, rather than from external perturbations that might otherwise produce misleading indications of chaos. Nonautonomous chaotic oscillators of this type have demonstrated considerable utility in areas such as cryptography and synchronization systems [4].

Keywords: Nonlinear circuits, chaos, hysteresis, chaotic oscillator, comparator

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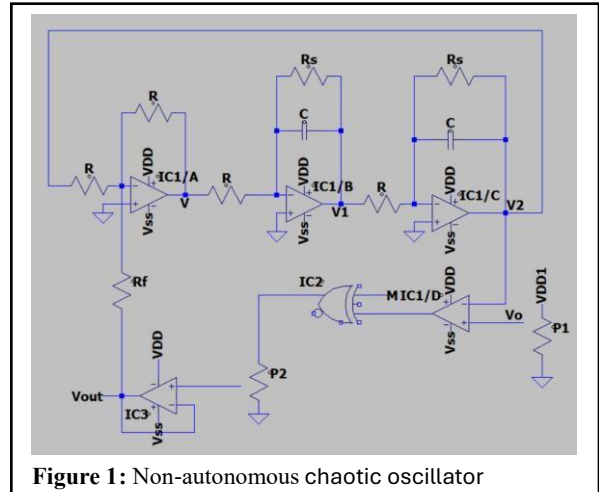


Figure 1: Non-autonomous chaotic oscillator

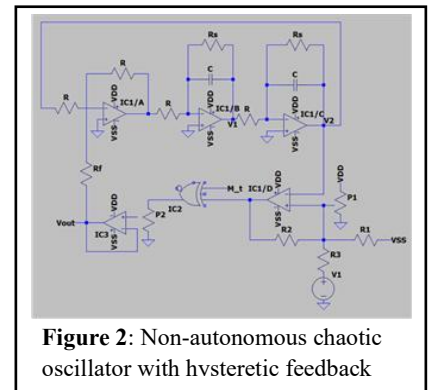


Figure 2: Non-autonomous chaotic oscillator with hysteretic feedback

Chaos and entanglement distillation in quantum protocols

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Extended abstract

Quantum entanglement can be distilled from multiple copies even by local operations and classical communication, inducing effective nonlinearity by post-selection [1]. Selecting exclusively a single outcome from the measurement results leads to an effective evolution which provides a pure quantum state outcome for pure input states. A small number of iterative applications of a well-designed protocol leads to a universal and practical entanglement distillation protocol in the small noise regime [2]. One of the Bell states is an attractive fixed point of the evolution, i.e. small noise in the initial state will eventually be diminished. A slightly distorted Bell state will be effectively purified in two iterations, while more general inputs with small incoherent noise in three iterations.

A related protocol with different local operations exhibits chaotic evolution for pure state inputs [3]. The border of the convergence regions in the parameter space of the initial states is characterized by a fractal. Noisy initial states alter the dynamics, without completely erasing the fractal until a critical noise level, similar to a single qubit analog of the two-qubit system [4-6]. The emerging phase transition is present in the two-qubit system when the initial quantum state's support is in a two-dimensional subspace.

Three-qubit GHZ states can be distilled with a similar protocol [7]. We discuss generalization of the entanglement distillation protocol for multi-qubit states as well. Our results indicate that chaotic evolution emerges for the generalized protocol with an arbitrary number of qubits.

Keywords: Iterated quantum protocols; Nonlinear quantum dynamics; Chaotic quantum evolution; Phase transition.

Acknowledgments

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Chaos-Enhanced Physical Unclonable Functions – A Review of Recent Developments

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Extended abstract

Physical Unclonable Functions (PUFs) authenticate hardware using unique device characteristics caused by minute random manufacturing variations. Classical designs such as arbiter PUFs can be broken by machine-learning (ML) attacks that predict responses with over 98% accuracy from a small set of challenge-response pairs [1]. Chaos-enhanced PUFs aim to mitigate this vulnerability by adding chaotic dynamics on top of the static manufacturing variation, which introduces additional entropy at run time [2]. Our work reviews recent chaos-based PUF designs. We propose a taxonomy that groups them into three families: chaotic-oscillator-enhanced arbiter PUFs [3], chaos-based digital PUFs, and hybrid or shuffled chaotic architectures [4, 5]. We exclude system-level chaos—PUF integrations, as well as a work on chaos-based ring-oscillator PUFs [6] that focuses on the use of the created responses as random numbers. Each design is measured using the framework of Maiti *et al.* [7] (in terms of uniqueness, reliability, uniformity, and bit-aliasing) along with reported ML attack resistance. Chaos-based designs resist ML attacks well; the reported prediction accuracy drops to 70% or lower, and three of the five tested designs reach about 50%, which is random guessing [3, 4, 5, 8, 9]. Most surveyed designs use simple chaotic elements, mainly the logistic map and Chua's circuit. The impact of higher-dimensional and continuous-time chaotic dynamics on chaos-based PUFs in terms of standard evaluation metrics remains an open research question.

Keywords: Chaos; Physical Unclonable Function; Machine-Learning Attacks; Prediction Accuracy.

Acknowledgments

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On the Physical Nature of Physical Unclonable Functions (PUFs): An Empirical Exploration of the Interplay Among Quantum Uncertainty, Chaos, and PUFs

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Extended abstract

The concepts of quantum uncertainty, classical chaos, and Physical Unclonable Functions (PUFs) are usually studied in different disciplines. Quantum mechanics describe the microscopic behaviour of matter, chaos theory describes deterministic but unpredictable nonlinear systems, and PUFs are hardware security primitives that exploit physical uniqueness. Despite these distinctions, all three can be understood as connected layers of physical reality. Quantum mechanics describe the fundamental interactions and behaviour of matter and energy at the smallest scales, where particles exhibit wave-like properties, exist in probabilistic states, and interact according to the principles of superposition, quantisation, and uncertainty. Chaotic dynamics amplify microscopic differences into macroscopic consequences, causing systems that begin in nearly identical states to evolve along dramatically different trajectories, making long-term prediction difficult despite the underlying laws being deterministic. PUFs exploit such amplified microscopic differences to create unique and measurable identities, leveraging unavoidable manufacturing variations and physical randomness to generate device-specific responses that are difficult to predict, replicate, or counterfeit. Understanding the relationship among these concepts offers a unified perspective on uncertainty, complexity, and physical identity.

At the most fundamental level, physical systems are described by quantum mechanics. Unlike classical mechanics, quantum theory does not assign simultaneously precise values to all observable physical properties. Instead, systems are described by a quantum state whose measurable properties are probabilistic. The uncertainty principle establishes limits on the simultaneous precision of complementary observables such as position and momentum. This uncertainty should not be interpreted as a limitation of measurement technology. On the contrary, in the standard interpretation of quantum mechanics, it reflects an intrinsic feature of physical reality itself. Consequently, microscopic physical processes, including atomic bonding, electron transport, diffusion, crystal growth, and semiconductor fabrication, are ultimately governed by quantum phenomena. Therefore, also the materials from which electronic circuits are constructed, are inherently shaped by quantum-scale processes. Although these effects are typically negligible at macroscopic scales, they provide a fundamental source of microscopic variation that might, among other things, contribute to the creation of PUFs and to the enhancement of chaotic behaviour.

Classical chaos arises in nonlinear dynamical systems that exhibit sensitive dependence on initial conditions. In such systems, arbitrarily small differences in the initial state can grow exponentially over time. Examples include weather systems [1], turbulent fluids, gravitational three-body systems, and nonlinear electronic circuits. It is important to state here that chaos is not equivalent to quantum uncertainty. Classical chaotic systems can be defined mathematically without reference to quantum mechanics. A hypothetical perfectly classical universe could still contain chaotic systems. Therefore, chaos is best understood as an emergent property of nonlinear dynamics rather than a direct consequence of quantum theory. However, in the real world, no physical system is perfectly classical. Every chaotic system is ultimately composed of quantum matter. As a result, microscopic uncertainties, including quantum fluctuations, thermal fluctuations, and material imperfections, can become amplified by chaotic dynamics. Chaos therefore acts as a bridge between microscopic uncertainty and macroscopic unpredictability. A useful distinction is that quantum mechanics provides the uncertainty, while chaos provides the amplification mechanism. The two phenomena are different but deeply connected.

Moreover, although chaotic systems appear random, their behaviour is not unconstrained. Chaotic trajectories often remain confined to bounded regions of phase space known as attractors. The apparent randomness emerges from complex motion within these constrained regions rather than unrestricted exploration of all possible states. A similar idea appears in quantum mechanics. A quantum state is represented by a wavefunction that assigns probabilities to possible measurement outcomes. Most of the theoretically available state space has negligible probability, while physically relevant outcomes are concentrated within specific regions. The same principle can be generalized to complex physical systems (such as PUFs [2]): their observable behaviour occupies only a small subset of all mathematically possible configurations [3]. In quantum systems, this subset is defined probabilistically. In chaotic systems it is defined dynamically through attractors and conservation laws. At the deepest level, the constraints on macroscopic behaviour originate from the underlying many-body quantum state and the physical laws governing interactions among particles. The chaotic phase space explored by a macroscopic system can therefore be potentially viewed as an emergent manifestation of deeper quantum constraints.

A Physical Unclonable Function (PUF) exploits microscopic manufacturing variations to generate a unique¹ hardware

¹ Thus, the term “Physical Unique Function” should be used to more accurately describe a PUF.

identity [4]. No two fabricated devices are physically identical because atomic-scale processes during fabrication produce slightly different structures. These differences become measurable through the electrical (or even optical – in general, physical) properties of the relevant structures, such as propagation delays, memory-cell biases, or oscillator frequencies. Traditionally, PUFs have been treated as static fingerprints. The relevant PUF device is assumed to possess a stable response, while noise and environmental effects are treated as small perturbations. However, an alternative perspective appears to be more accurate. Instead of viewing a PUF as a fixed object, it may be viewed as a high-dimensional physical system whose internal state evolves over time [5]. The measured response then becomes a projection of a much larger hidden state. From this perspective, drift, aging, and noise may represent motion through a constrained state space rather than purely random disturbances. This interpretation does not imply that all PUFs are chaotic. Most practical PUFs are engineered to remain somewhat stable. Nevertheless, most classes of structures involved tend to somehow exhibit behaviour that resembles motion through a bounded dynamical landscape, with multiple measurements over long periods of time leading to time series that somehow resemble chaotic behaviour.

Thus, a somehow unified picture emerges by considering a hierarchy of physical processes:

1. Quantum mechanics governs microscopic matter.
2. Microscopic variations become embedded in physical structures.
3. Nonlinear dynamics amplify microscopic differences.
4. Macroscopic systems explore constrained regions of state space.
5. PUFs exploit these unique physical trajectories and structures as identities.

Within this framework, a PUF measurement can be interpreted as a snapshot of an evolving physical process. The observable response does not reveal the full internal state but only a projection of it. In this respect, PUF measurements resemble observations of both quantum systems and chaotic systems: a single observation provides only partial information about a much richer underlying structure.

Quantum uncertainty, chaos, and PUFs should not be regarded as identical phenomena. Quantum uncertainty is a fundamental property of microscopic physics, while chaos is an emergent feature of nonlinear dynamics. Nevertheless, they are connected through the amplification of microscopic differences into macroscopic behaviour. PUFs occupy an interesting position within this hierarchy because they transform microscopic physical uniqueness into observable and useful identities. Viewed in this way, PUFs are not merely hardware fingerprints. They are manifestations of a deeper physical process in which quantum-scale phenomena, material structure, and nonlinear dynamics combine to produce unique, bounded, and observable patterns in the macroscopic world.

Keywords: Physical Unclonable Function; Chaos; Quantum Uncertainty; Physical Unique Function; Phase Space; State Space; Time Series.

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This work has been partially funded by the German Research Foundation – Deutsche Forschungsgemeinschaft (DFG), as part of the Young Scientist Projects “Security Applications of Printed Electronics” and “Machine-Learning-Augmented Chaotic Memristive PUFs for Printed-Electronics Security” of the Priority Program – SchwerpunktProgram (SPP) 2253: “Nano Security: From Nano-Electronics to Secure Systems”.

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Cationic lyotropic liquid crystalline nanoparticles for drug delivery: how the morphological complexity leads to multi-functionality

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Extended abstract

Lyotropic liquid crystalline nanoparticles are promising drug delivery nanocarriers, exhibiting significant technological advantages, such as their extended internal three-dimensional morphology of high grade of complexity. In this study, cationic non-lamellar lyotropic–lipidic liquid crystalline nanoparticles were formulated by phytantriol lipid. The poly(2-(dimethylamino)ethyl methacrylate)-*b*-poly(lauryl methacrylate) block copolymer carrying tri-phenyl-phosphine cations (TPP-QPDMAEMA-*b*-PLMA), was employed as a stabilizer co-assisted by other polymeric guests, both block copolymers and gradient copolymers. The exact qualitative and quantitative formulation of the systems was investigated. Their physicochemical profile was depicted from a variety of light scattering techniques, including their fractal dimension assesment, while their microenvironmental parameters were determined by fluorescence spectroscopy using adequate probe molecules. The effect of environmental conditions was monitored, confirming stimuli-responsiveness properties. Their both external and internal morphology was illustrated by cryo-TEM, revealing expanded internal assemblies. Resveratrol was incorporated into the nanoparticles and the entrapment efficiency was calculated. Their properties were found to be dependent on the formulation characteristics, such as the lipid used, as well as the architecture of the polymeric stabilizer, also being found to be stealth toward proteins, exhibiting stimuli responsiveness and high entrapment efficiency. The different polymeric combinations played a crucial role in the morphology of the nanosystems, wherein a prevailing population of compact structures with a high internal organization was found, probably due to the effect of the phytantriol lipid. This newly proposed PHYT lipid–copolymer combination yielded to a new morphologically combined nanoparticulate structure of a well-defined liquid crystalline nanoparticle of $Pn3m$ symmetry, being embedded in a plethora of large intersecting lamellas. Moreover, this newly proposed PHYT lipid–copolymer combination provoked a decrease in empty vesicle population within the dispersion, and an increase in the organized structures. This result embraces all the advantages of the liquid crystalline nanostructures versus the empty ones, like the enhanced loading capacity. In conclusion, the studied liquid crystalline nanoparticles, being stimuli-responsive, with high cationic potential, high loading capacity and showing intriguing 3D structures, are suitable for pharmaceutical applications.

Keywords: lyotropic liquid crystals; drug delivery nanosystems; cubosomes; cryo-TEM; internal morphology

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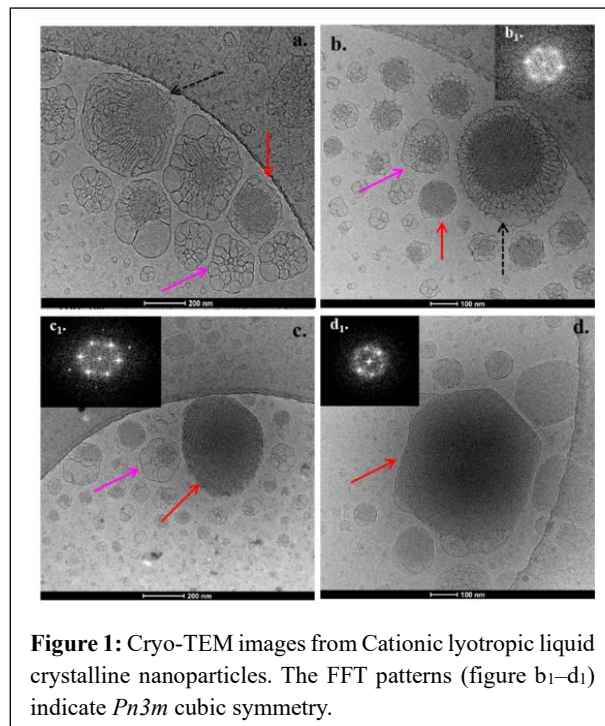


Figure 1: Cryo-TEM images from Cationic lyotropic liquid crystalline nanoparticles. The FFT patterns (figure b₁–d₁) indicate $Pn3m$ cubic symmetry.

Stimuli-responsive lyotropic liquid crystals for drug delivery: the relationship between internal structural complexity and drug release kinetic

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Extended abstract

The abilities of sub-cellular targeting and stimuli-responsiveness are critical challenges in pharmaceutical nanotechnology. In the present study, glyceryl monooleate (GMO)-based non-lamellar lyotropic liquid crystalline nanoparticles were stabilized by the poly(2-(dimethylamino)ethyl methacrylate)-*b*-poly(lauryl methacrylate) block copolymer carrying tri-phenyl-phosphine cations (TPP-QPDMAEMA-*b*-PLMA), either used alone or in combination with other polymers as co-stabilizers. The stabilizer is composed of the stimuli-responsive PDMAEMA blocks that were partially quaternized by the delocalized cation TPP. The systems were designed to perform simultaneously sub-cellular targeting, stimuli-responsiveness and to exhibit stealthiness. The physicochemical characteristics and fractal dimensions of the resultant nanosystems were obtained from light scattering techniques, while their micropolarity and microfluidity from fluorescence spectroscopy. Their morphology was assessed by cryo-TEM, illustrating complex structures of high grade of internal organization. The analyzed properties, including the responsiveness to pH and temperature, were found to be dependent on the combination of the polymeric stabilizers. The subcellular localization was monitored by confocal microscopy, revealing targeting to lysosomes. Subsequently, resveratrol was loaded into the nanosystems, the entrapment efficiency was investigated and *in vitro* release studies were carried out at different conditions, in which a stimuli-triggered drug release profile was achieved. The morphological re-arrangements to disorganized, bulgy structures, observed by cryo-TEM analysis, in response to pH and temperature changes, are also reflected by the higher drug release levels at such conditions. We assume that these stimuli-induced re-arrangements can promote drug release. The systems exhibited a pH-induced ζ -potential conversion to increased positive values in acidic conditions and decreased positive values at a physiological pH. This property can be exploited for the intracellular accumulation of the nanosystems and the complexation with subcellular organelles. Furthermore, the combinations of the polymers utilized prevented the disintegration of the nanoparticles by serum proteins, yielding a possible increase of stealthiness. The fractal dimension, as well as the R_g/R_h ratio, obtained by SLS data indicated pH- and thermo- induced morphological/structural rearrangements that were also confirmed by cryo-TEM results. In conclusion, the proposed multi-functional nanosystems can be considered as potentially stealth, stimuli-responsive drug delivery nanocarriers, with targeting ability to lysosomes and presenting a stimuli-triggered drug release profile.

Keywords: lyotropic liquid crystals; drug delivery nanosystems; cubosomes; cryo-TEM; internal morphology

Acknowledgments

This research is co-financed by Greece and the European Union (European Social Fund—ESF) through the Operational Programme: Human Resources Development, Education and Lifelong Learning, in the context of the project, Strengthening Human Resources Research Potential via Doctorate Research—Second Cycle (MIS-5000432), implemented by the State Scholarships Foundation (IKY).

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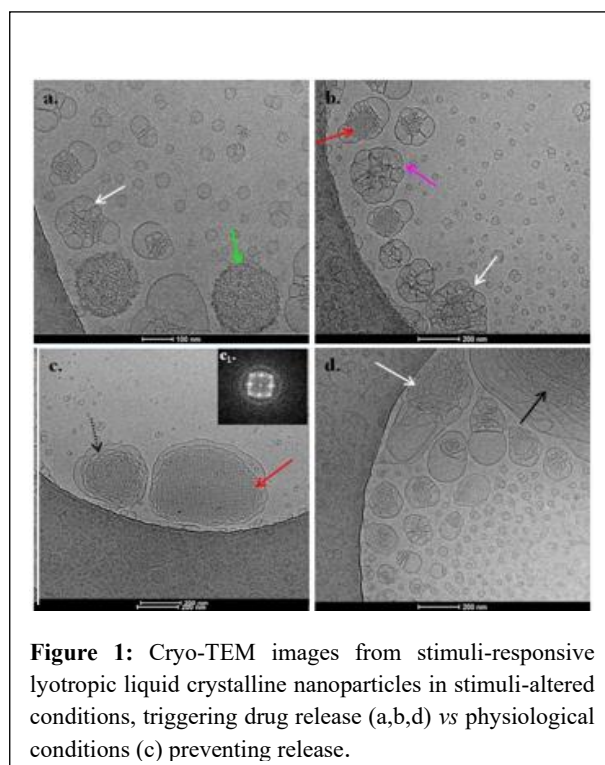


Figure 1: Cryo-TEM images from stimuli-responsive lyotropic liquid crystalline nanoparticles in stimuli-altered conditions, triggering drug release (a,b,d) vs physiological conditions (c) preventing release.

Learning by Self-Organization in Laser-Driven Dissipative Nanopatterns

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Extended abstract

How can one design complex systems capable of learning a given functionality? We address this question in the context of ultrafast laser–surface interaction, where repeated irradiation drives a metallic surface far from equilibrium and progressively generates self-organized nanoscale patterns. Under cross-polarized femtosecond double pulses, an initially smooth nickel surface evolves from pulse to pulse. At each irradiation step, light interacts with the morphology inherited from earlier exposures, and the absorbed energy then reshapes the surface that will be exposed next. The mechanism is therefore a feedback loop between electromagnetic absorption, thermoconvective instability, hydrodynamic motion in the transient molten layer, and resolidification. This loop provides a physical route toward structural memory.

Our key result is that light-induced imprints encode the excitation history. They retain local signatures of laser-field polarization and form a cooperative organization of surface reliefs that enhances absorption. Once the unstable molten layer resolidifies, this curvature network is frozen into the material, so that the surface geometry stores memory of previous irradiations and modifies future optical absorption.

To reveal this mechanism, we combine electromagnetic simulations and machine-learning-based absorption prediction with statistical measures of surface complexity. The absorbed energy is evaluated on the evolving surface topographies, while pattern complexity is quantified through a measure balancing entropy and disequilibrium. The evolution shows that optical response and morphology shape one another. During the learning regime, complexity drives absorption, and absorption fuels complexity: absorbed energy and pattern complexity increase together as the system first responds to irradiation, then enters an iterative self-organization phase, and finally reaches a memory-stabilization phase where the structured morphology preserves an enhanced optical response. Beyond a critical exposure, however, the system enters a destructive or chaotic regime: excessive local absorption degrades the organized patterns and breaks the correlation between complexity and absorption.

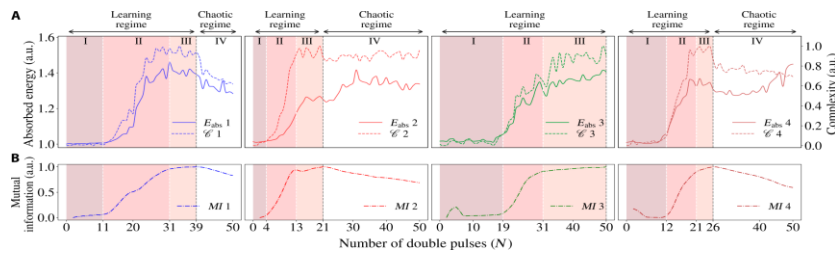


Fig 1: Co-evolution of absorbed energy and surface complexity with the number of laser pulses, revealing learning, memory stabilization, and destruction regimes in laser-induced dissipative nanopatterns.

This provides a concrete example of learning in an inanimate dissipative system. The material does not learn through an external algorithm, but through nonlinear physical feedback: surface features that enhance absorption are reinforced by subsequent irradiations, while less efficient configurations are not amplified in the same way. The resulting trajectory is history-dependent, functional, and adaptive. By showing that complexity, memory, and optical absorption co-evolve, this work connects laser-induced self-organization with broader learning dynamics in complex systems.

Keywords: photonic learning; structural memory; laser-induced nanopatterns; self-organization; complexity.

Acknowledgments

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Chaotic Dynamics of the Tumor Microenvironment in Triple-Negative Breast Cancer: A Review of Exosome-Mediated Macrophage Polarization as a Nonlinear Regulatory Axis

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Extended abstract

Introduction. Triple-negative breast cancer (TNBC) is the most aggressive breast cancer subtype, defined by the absence of ER, PR, and HER2 expression and characterized by high metastatic potential and a chaotic genomic profile. A fundamental feature of TNBC is its tumor microenvironment (TME), which functions as a nonlinear chaotic system where small perturbations in intercellular communication networks and cytokine gradients can lead to dramatic outcomes in tumor progression [1], [2].

Chaos Theory and the TME. Chaos theory describes deterministic systems that are exquisitely sensitive to initial conditions [3]. In the TME, a minor shift initiated by a single exosomal signaling molecule can, through the butterfly effect, transform the entire system into an immunosuppressive ecosystem. The transitions of tumor-associated macrophages (TAMs) between antitumoral M1 and pro-tumoral M2 phenotypes can be conceptualized from a dynamical systems perspective as "competing attractors". In TNBC, the system trajectory converges toward a stable M2-dominant "strange attractor" that sustains immune evasion [4].

Exosomes as Nonlinear Regulators. Cancer cell-derived exosomes (30–150 nm) are powerful tools that functionally reprogram macrophages through the microRNA and protein cargoes they carry [5]. This communication operates via nonlinearly interacting pathways such as the JAK/STAT, PI3K/AKT, and NF-κB cascades, rendering the system's behavior unpredictable. Literature studies confirm that TNBC-derived exosomes shift macrophage fate toward the M2 phenotype, reinforcing the immunosuppressive TME through a self-amplifying feedback loop [6], [7], [8].

Synthesis and Conclusion. This review demonstrates that the TNBC microenvironment constitutes a biologically chaotic system and that exosome-mediated macrophage polarization represents a critical nonlinear regulatory axis within this system. Understanding TME dynamics through complex systems theory offers novel therapeutic opportunities by disrupting the exosome-M2 axis with targeted perturbations to redirect the system back toward an antitumoral state. The integration of mathematical modeling and multi-omics analysis will be essential to decode this complexity in TNBC.

Keywords: Triple-Negative Breast Cancer; Tumor Microenvironment; Macrophage Polarization; Exosomes; Chaos Theory.

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Treasure Model: Collective Intelligence fingerprints of LLM Agents

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Extended abstract

Large Language Models (LLMs) are increasingly deployed as autonomous agents in multi-agent networks, where they clearly exhibit collective intelligence. While there have been numerous attempts to qualitatively assess this collaboration [1][2][3][4], there remains a critical need for rigorous, mechanistic models. In this work, we present the “Treasure Opening Model” (TOM), a mechanistic framework to numerically and unbiasedly quantify the collaborative capacity of an LLM swarm. We arrange 100 LLM agents in a small world network ($k=6$). Each agent i possesses an initially corrupted alphanumeric sequence $s_i(t)$ of fixed length N , with a minimum corruption rate of 30%. The collective goal given to each LLM agent is to find the uncorrupted sequence s^* to open a “treasure box”. They must cooperate to assemble the right sequence hidden in the distributed collective information. The obtained collective information refinement dynamics allow us to study swarm behavior from both macroscopic and microscopic perspectives. In particular, we observe that the system exhibits a distinct critical length N_c for the sequences used in the simulation, which is typical of the LLM model used for collective truth-seeking. Figure 1 in particular describes the dynamics that explain the existence of this critical length. Each LLM has a different capability to condense the diversity of information present in the collective network into useful information before the information landscape collapses and the truth becomes unreachable. Our model can quantify the reason for such different behavior between different LLM models at a lower level. We introduce a set of fingerprints parameters that constitute the collective cognitive signature of each LLM model. Figure 2 shows that the behavior of each model can be defined in terms of Copy (C), the propensity of the model to copy the sequences of its neighbors, thereby reducing diversity; Selection (S), the capability to select the right neighbors and only the useful information; and Inertia (I), the tendency of a model to be stubborn and keep the sequence unchanged. These parameters are LLM model-dependent and allow us to characterize the collective behavior of a model numerically. N_c and these parameters characterize the collective intelligence of a model. This is independent of the amount of information; rather, it depends on how efficiently they convert diversity into a correct consensus before it collapses.

Keywords: Swarm; Collective Intelligence; LLM; Multi agents; AI.

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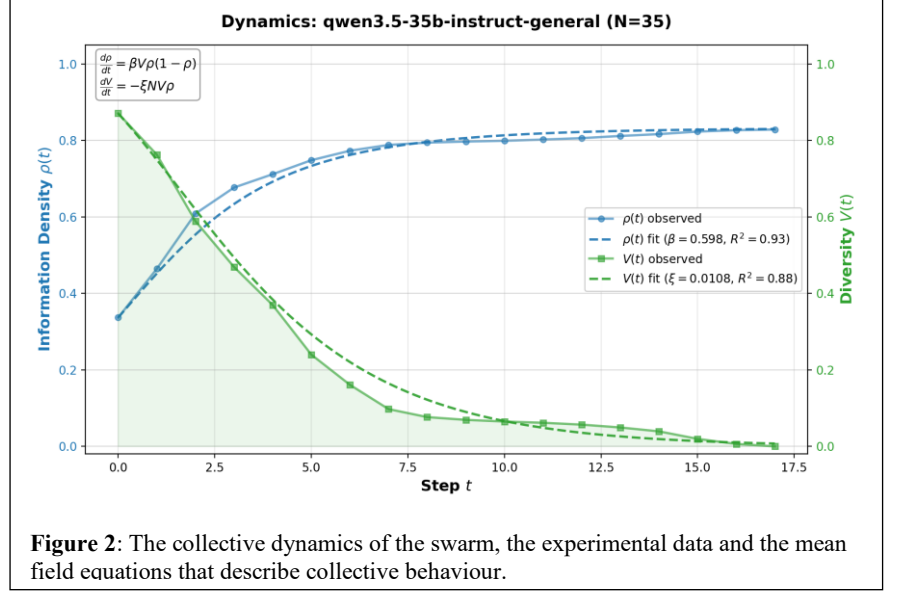


Figure 2: The collective dynamics of the swarm, the experimental data and the mean field equations that describe collective behaviour.

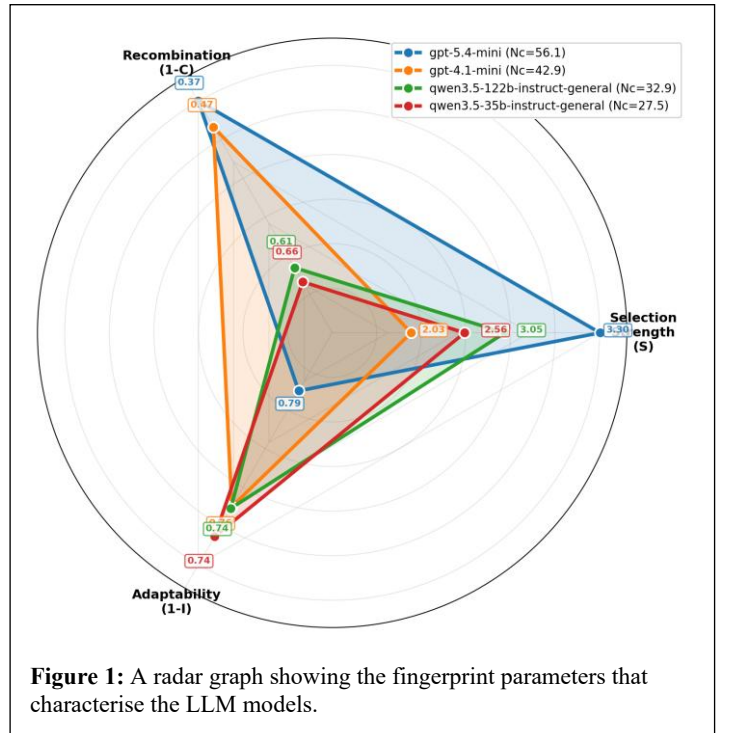


Figure 1: A radar graph showing the fingerprint parameters that characterise the LLM models.

The roughness paradox: Quantification of randomness in rough surfaces

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Extended abstract

Roughness is a common feature of the most surfaces found in both nature and laboratory, spanning a broad spectrum of scales—from the macroscale of mountains and hills to the micro- and nanoscale of engineered nanostructures. In the latter case, it plays a critical role in determining surface properties such as optical reflectance, wettability, tribological behavior, biological adhesion to name just a few. Beyond its technological relevance, a rough surface constitutes a complex, nonequilibrium system in which order and randomness coexist in multiple ways challenging its theoretical understanding and mathematical characterization. This tension between ubiquity and conceptual elusiveness is often referred to as the *roughness paradox*. In this work, we aim to contribute to its deeper investigation by focusing specifically on the role of randomness in shaping the complexity of rough surfaces.

A widely accepted classification of rough surfaces distinguishes between self-affine fractal surfaces and mound-type surfaces. This distinction is based on the presence or absence of a characteristic scale in surface morphology. Self-affine surfaces are scale-free and exhibit anisotropic self-similarity, whereas mound surfaces are dominated by a characteristic scale that defines the average size or spacing between surface mounds. In idealized cases, both surface types display perfect symmetry—either scale invariance in self-affine surfaces or translational symmetry in mound surfaces. However, real surfaces observed in laboratory often exhibit stochastic deviations from these ideal symmetries. For self-affine surfaces, multifractal formalism has been developed to quantitatively assess such deviations. In contrast, no systematic framework currently exists to address randomness in mound-type surfaces. This work aims to begin bridging that gap.

To this end, we explore two questions. First, how can we define, characterize and model these random deviations? Secondly, what are the proper mathematical tools which can “sense” these deviations? How can the conventional approaches based on Fourier transform and correlation analysis detect and quantify these deviations?

To address the first question, we develop a mathematical framework and modeling tools to generate synthetic surfaces exhibiting specific mound morphologies with controlled deviations from perfect periodicity. A key conceptual distinction is made between two types of randomness: positional and shape/size randomness. Positional randomness refers to stochastic deviations of mound locations from their ideal symmetrical positions, without altering their geometric characteristics. In contrast, shape/size randomness involves variations in the morphological attributes of the mounds—such as height, width, or curvature—while preserving their spatial arrangement. These types may have different material and process origins and therefore the quantification of their contribution may disclose critical information about the factors that dominate in surface shaping. In relation to the second question, we investigate how these two forms of randomness influence the Fourier spectrum and the spatial correlation function. The objective is to identify which features of these analytical tools are most sensitive to positional versus shape/size variability in mound-structured surfaces. Our approach begins with the analysis of synthesized surfaces, where both the type and magnitude of randomness are precisely controlled. We then extend our investigation to experimentally obtained surfaces with mound-like topographies, specifically those produced through polymer film etching.

Keywords: surfaces, roughness, modeling, Fourier analysis, correlation function

Real World Memristor-Inductor-Capacitor Oscillator

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Extended abstract

Memristor has been proposed and considered as the fourth fundamental passive circuit element, alongside resistor, capacitor, and inductor [1]. Its main property is that its resistance is dependent on the history of the applied voltage across or the current through it. This means that it behaves as a resistor that remembers its past state, ideally, even after the power is removed. Hence the name memristor (resistor with memory).

In 2002, the inventor Alex Nugent together with the investor Hillary Riggs founded KnowmTech LLC. In 2018, the company began developing its own memristor technology, finally producing a series of memristor devices, having many advantages and disadvantages, but being one of the first off-the-shelf memristors. As a model, the total current flowing through a Knowm memristor consists of two components: I_m , which represents the memory current and is associated with the main memristive mechanism, and I_s , which corresponds to the current of a Schottky diode placed in parallel with the mechanism generating I_m [2]. In Figure 1 a typical, experimental though, I-V characteristic appears. The I-V reveals a pinched hysteresis loop passing through the origin, which is a key signature of memristive behavior. The nonlinear behavior of such devices has also been linked to complex dynamical phenomena, including chaos in nonlinear circuits as demonstrated in [3].

On the other hand, a Resistor-Inductor-Capacitor (RLC) circuit (second-order electrical circuit) is demonstrating a known electric, dynamic behavior ruled by the exchange of energy stored in a magnetic and an electric field; its response being strongly frequency dependent. This makes RLC circuits a standard model for analyzing oscillatory behavior and frequency sensitive phenomena in electrical systems.

In this study, a nonlinear oscillator, appearing in Figure 2, is being shown. In this circuit a Memristor-LC (MLC) topology is experimentally investigated. An off-the-shelf memristor (Knowm) acts as a nonlinear component, in fact a resistor with memory, and is responsible for the circuit's chaotic behavior. The circuit is a non-autonomous one, driven by an external oscillations' generator. It should be noted that the resistor R1 is utilized for limiting the current through the circuits, thus, the memristor itself, while it is utilized for monitoring the current through the memristor device. The circuit has been investigated with reference to its dynamic behavior dependence on the frequency driving the circuit focusing on chaotic behavior and the existence of specific routes to chaos. The circuit's experimental setup appears in Figure 3.

This experimental investigation of the MLC circuit highlighted significant and multifaced characteristics, that arise from the coexistence of linear and nonlinear elements within a dynamical system. Although the studied circuit implements a very elementary topology; it exhibits rich chaotic behavior. The conductive state of the memristor, and further of the whole circuit, does not remain constant depending on the integral of the current that has flown through it; that is, on the time history of the excitation. For low frequency drive, the system showed a periodic response. As the frequency increased, bursts of chaotic behavior appeared, becoming more frequent tending to an increasingly robust deterministic chaotic behavior, as the system is transitioned from a periodic state to a chaotic one. The resulting chaotic mode of operation is illustrated in Figure 3, where a chaotic attractor formed in the

I-V phase portrait, appears. It is apparent that an intermittency route to chaos emerges, due to the circuit's sensitivity to initial conditions as this is combined with the temporal evolution of the external excitation of the circuit.

Concluding, the emergence of chaos, intermittency, and nonlinear phenomena makes this circuit particularly useful for theoretical study; since, understanding the MLC dynamics contributes to innovative technological approaches in electronics, computing, and neuroscience.

Keywords: Memristor, nonlinear circuits, nonlinear oscillators, Memristor-Inductor-Capacitor (MLC) circuit

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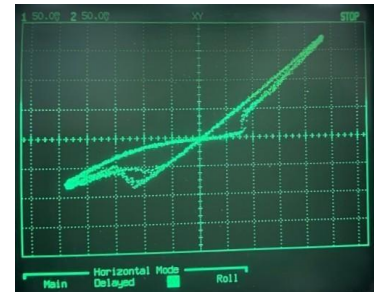


Figure 1: Experimental I-V curve of

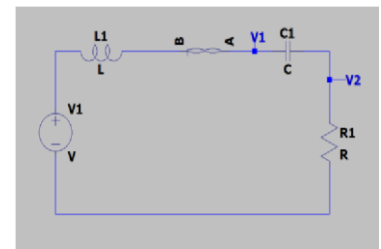


Figure 2: The MLC oscillating topology.

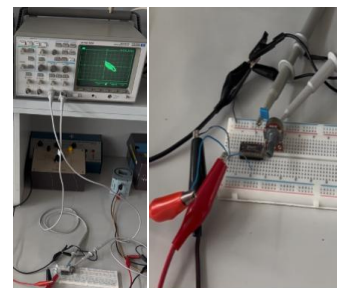


Figure 3: The experimental MLC oscillating topology.

Clinical Trials Complexity: Assessment and recommendations for reduction

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Extended abstract

Randomized controlled clinical trials have become more complex over the past decade, as they often involve more countries, more enrolled patients, more investigational products, and higher costs per patient [1]. Recent developments in biomarker discovery and changes in regulatory frameworks have further added to this complexity. Tools such as the Protocol Complexity Tool (PCT) [2] aim to assess trial complexity and help stakeholders identify the main contributing factors, as well as possible areas where complexity could be reduced. However, while such tools are important, they often do not provide a structured recommendation framework for reducing complexity. As a result, the identification of potential burdens is left largely to human judgment, and some sources of complexity may remain hidden or difficult to recognize during trial planning.

In this work, we propose an AI-driven decision-support system that combines Large Language Models with an agentic workflow that recommends changes to the trial protocol to reduce its complexity. The system uses as inputs the trial protocol, the outputs of a complexity assessment tool, and a knowledge base of prior trial protocols with related objectives. It compares the complexity profile of the target protocol with those of similar prior trials retrieved from the knowledge base, considering both study design characteristics and comparable complexity profiles. Based on this comparison, the system generates targeted and feasible recommendations for protocol improvement. Rather than proposing generic optimizations, it prioritizes changes that are realistically actionable within the scientific, clinical, and operational constraints of the study. The framework also implements human-in-the-loop review checkpoints to ensure that the proposed protocol changes remain clinically appropriate and aligned with user judgment. Planned validation includes retrospective comparison of system recommendations against documented amendment patterns in completed trials, complemented by expert clinical-operations review of recommendation quality and feasibility. Overall, the system aims to help trial teams translate complexity assessment outputs into protocol changes that are scientifically justified and operationally acceptable.

Keywords: Clinical trial complexity, Randomized controlled trials, AI Agents, Human-in-the-loop, Decision Support.

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The Reversibility Error Method to identify chaos from order in non-Hamiltonian conservative dynamical systems

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Extended abstract

Distinguishing between regular and chaotic behavior remains a challenging task. Although the Lyapunov Characteristic Indices are dominant in the literature, new indices and methods that identify the nature of each system are introduced [1]. One such method is the Reversibility Error Method (REM), introduced by F. Panichi, L. Giotti, K. Gózdziwski, and G. Turchetti [2,3].

REM is based solely on trajectory computation, not on the variational vectors, and so it is a reliable and straightforward method. Until now, REM has been used in symplectic maps and Hamiltonian systems [4, 5]. In this work, we apply REM using a proper numerical solver to non-Hamiltonian, non-symplectic conservative systems, thereby extending the method to a broader class of conservative systems.

Keywords: Chaos index; Reversibility Error;

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Comparative Analysis of Classical Machine Learning and Deep Learning Methods for Hourly Solar Irradiance Forecasting Under Walk-Forward Evaluation

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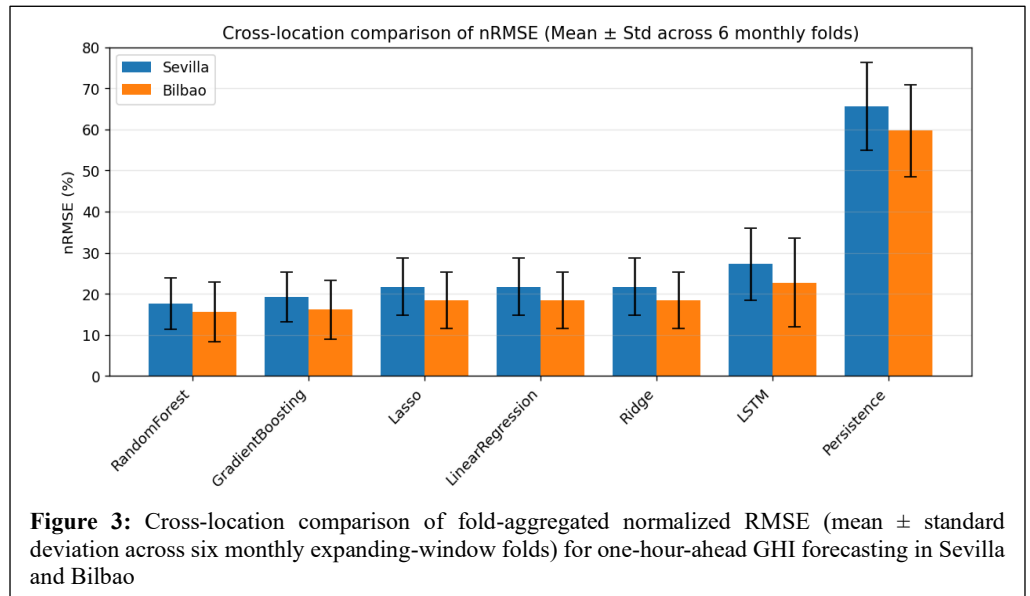
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Extended abstract

Accurate short-term solar irradiance forecasting is an important aspect for the utilisation of photovoltaics in modern power systems. Uncertainty in forecasting in such systems could lead to poor planning, inefficient reserve management, and grid instability. This study focused on a comparative analysis of different forecasting techniques for one-hour-ahead solar irradiance forecasting.

The methods compared are baseline methods, classical machine learning models and deep learning models. Two different Spanish locations, i.e., Sevilla and Bilbao, were used to avoid climatic dependence in the study. Data was obtained from the Photovoltaic Geographical Information System (PVGIS) from January 2022 to January 2025. The methodology involved preprocessing, feature engineering and expanding-window walk-forward evaluation to ensure temporal consistency and a fair comparison across different models. To establish a reference for evaluation and performance, baseline models were used. The used model is a persistence model, which assumes future irradiance equals the most recent observed value, and moving-average models computed over historical windows.

The classical machine learning models evaluated in this study are linear regression, ridge regression, lasso regression, random forest regression and gradient boosting regression. Long short-term memory (LSTM), a deep learning model, was evaluated against the performance of these classical machine learning models. The objective of the study was to accurately predict the future hourly solar irradiance values based on historical data. An expanding-window-walk-forward backtesting procedure was used to evaluate the temporal



robustness of the models. In this approach, the dataset is divided into sequential monthly folds. For each fold, models are trained on all historical observations up to the beginning of a given month and evaluated on the subsequent month.

Final reported results correspond to the mean and standard deviation of performance metrics across the retained folds. Classical machine learning models, Random Forest and Gradient Boosting, show better performance than LSTM and baseline models for both locations. Random forest achieved the best results with mean RMSE values of 59.71 W/m² for Sevilla and 77.02 W/m² for Bilbao, followed by Gradient Boosting. In comparison, the LSTM model produced higher mean RMSE values of 92.59 W/m² and 113.16 W/m² for Sevilla and Bilbao, respectively. Although absolute forecasting error increases under the more variable maritime conditions of Bilbao, the relative ranking of models remains stable. These findings indicate that, for one-hour-ahead irradiance forecasting based on structured hourly tabular features, carefully engineered classical machine learning models provide a stronger balance of accuracy, robustness, and practical deployability than more complex recurrent deep learning architectures.

Keywords: Solar irradiance forecasting; global horizontal irradiance; machine learning; LSTM; walk-forward evaluation

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Physics-Informed Neural Networks and Symbolic Regression as Explainable AI Surrogates in Wall-Bounded Turbulence

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Extended abstract

Introduction. Wall-bounded turbulent flows are highly chaotic systems difficult to predict using standard Navier-Stokes equations. To bypass these high computational costs, artificial intelligence (AI) offers a promising alternative for modeling turbulent statistics. This work integrates Physics-Informed Neural Networks (PINNs) and Symbolic Regression (SR) with high-fidelity Direct Numerical Simulation (DNS) data. By applying this framework to a standard channel flow, we develop explainable, adaptable surrogate models that accurately capture chaotic near-wall dynamics.

Methodology. At first, a hybrid optimization PINN pipeline calibrates the constants of the logarithmic law (von Kármán constant κ , additive B) and the bounds of its validity region (y_{low}^+, y_{high}^+) directly from DNS data, and hard-codes them into a PINN whose loss enforces the Reynolds-averaged Navier-Stokes (RANS) equations together with the identified log-layer [1]. Next, learnable physics is embedded directly in the loss: a DNS-calibrated PINN with trainable von Kármán κ and van Driest damping constant A^+ takes $[\eta = y^+/Re_\tau, Re_\tau]$ as inputs and extrapolates the inner-law velocity profile up to $Re_\tau \approx 10,049$ from training data restricted to $Re_\tau \leq 4186$ [2]. Finally, Reynolds-number-adaptive SR distills the DNS statistics into explicit closed-form expressions for the mean velocity across the viscous, buffer and logarithmic regions, in both a global (SR_w) and a Reynolds-specific (SR_w^{Re}) formulation [3].

Results and Discussion. These approaches suggest that the chaotic, multiscale near-wall dynamics can be reconstructed by physics-constrained AI surrogates that match DNS qualitatively and quantitatively, at orders-of-magnitude lower computational cost. PINNs calibrated with learnable closure constants remain stable in the extrapolation regime, suggesting that the apparent universality of wall turbulence is encoded in a small set of slowly varying parameters that AI can autonomously recover from data. Symbolic regression, in turn, reveals the functional form behind these parameters, bridging black-box learning and classical turbulence theory, and outperforming traditional log-law and damping-based formulations precisely in the buffer and transition regions where chaotic activity is strongest and where universal scaling tends to break down.

Conclusions. Coupling Physics-Informed Neural Networks and Symbolic Regression with DNS creates an explainable, physically based framework for studying the chaotic dynamics of wall-bounded turbulence. By delivering interpretable governing equations in place of black-box predictions, this methodology paves the way for AI-driven discovery in chaotic transport and offers an adaptable framework for next-generation CFD workflows and digital twins.

Keywords: Wall-bounded turbulence; Chaotic dynamics; Physics-Informed Neural Networks; Symbolic Regression; Explainable AI.

Acknowledgments

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Comparative Analysis of Biometric Modalities for Smart Home Authentication: Face, Iris, Voice, and Fingerprint under Machine Learning and Deep Learning Approaches

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Extended abstract

Smart home environments increasingly rely on biometric authentication to balance convenience with security, yet biometric deployments often differ considerably under similar conditions. While face, iris, voice and fingerprint are commonly used as authentication options, their behavior in real households rarely matches device specifications. Users respond to each modality through local routines, perceptions of intrusiveness and varying levels of trust, all of which shape authentication success in practice. The choice of a biometric trait therefore cannot be reduced to recognition accuracy alone, but also involves trade-offs in user acceptance, hardware cost, environmental robustness and deepfake resistance. This study compares face, iris, voice and fingerprint for smart home authentication and aims to map their trade-offs across quantitative and qualitative criteria rather than identifying a single winner. The work is based on a comparative empirical analysis using four publicly available datasets—Extended Yale Face Database B, CASIA-Iris-Interval, LibriSpeech dev-clean and SOCOFing—modelling a smart-home household with twenty registered members for face and iris, thirty speakers for voice, and a fifty-subject HARD fingerprint protocol with one Real enrolment scan per user. In total, 1,300 face images (sixty-five per subject), 428 iris images (twenty to forty per subject), 450 speech clips (fifteen per speaker, up to four seconds each) and 156 fingerprint images (fifty enrolment scans plus 106 altered-hard test samples) are used. Classical machine-learning baselines and a deep model per modality are evaluated with stratified 5-fold cross-validation for classical ML on face, iris and voice (Accuracy, Precision, Recall, F1, FAR, FRR), plus a separate fingerprint HARD hold-out (one Real enrol scan, Altered-Hard test), complemented by literature-derived qualitative scores for user acceptance, cost, environmental robustness and deepfake resistance. Results indicate that deep learning does not uniformly outperform classical machine learning: transfer learning benefits some image-based modalities under limited enrolment, whereas hand-crafted descriptors remain highly competitive, particularly for fingerprint authentication under an out-of-distribution HARD protocol with a single genuine enrolment scan. No modality dominates all criteria: face combines strong accuracy with the highest user acceptance but the lowest deepfake resistance; iris resists spoofing yet remains costly and intrusive; voice and fingerprint offer moderate cost but degrade under noise or wet-finger conditions. These observations suggest that smart home authentication should be assessed not only as an accuracy problem but as a multi-criteria design space shaped by security, cost, usability and context. By combining quantitative evaluation with qualitative criteria, the study offers a comparative framework for choosing, or fusing, biometric modalities in smart home settings.

Keywords: Biometric authentication; Smart home; Deep learning; Machine learning comparison; Multimodal fusion.

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Stability Analysis of Physics-Informed Neural Networks for Stiff Linear Differential Equations

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Extended abstract

We present a stability analysis of Physics-Informed Neural Networks (PINNs) coupled with random projections, for the numerical solution of (stiff) linear differential equations. For our analysis, we consider systems of linear ODEs, and linear parabolic PDEs. We prove that properly designed PINNs offer consistent and asymptotically stable numerical schemes, thus convergent schemes. In particular, we prove that multi-collocation random projection PINNs guarantee asymptotic stability for very high stiffness and that single-collocation PINNs are stable. Applications in data-driven dynamical systems modelling are discussed

This is joint work with G. Fabbiani, C. Siettos and E. Bollt



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