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Editorial

Festschrift on the occasion of Ulrike Feudel's 60th birthday

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Abstract. Not expected for editorial (?)

Since the early days of chaos theory [1] and complexity research [2] and the boom of results obtained in the 1990s, we have witnessed a growing body of work on applications of nonlinear dynamics, chaos and complexity in diverse fields of science, e.g., neuronal dynamics and brain research, laser dynamics or excitable media in chemistry, or the dynamics of ecological populations or communities, to mention but a few. On the one hand, these applications fueled a revived interest in and enlarged perspective on synchronization phenomena in oscillatory systems. On the other hand, they inspired to investigate effects of the coupling topology in networks where each node represents a subsystem with an intrinsic nonlinear dynamics; between the classical extremes of next neighbor coupling (diffusive) and the global all-to-all coupling (mean field) interesting new phenomena can be found as, for instance chimera sates that have come into focus of research recently. While chaos is often defined and observed in deterministic nonlinear dynamics the importance of temporal fluctuations and noise is widely acknowledged and, in particular, cooperative action of noise and nonlinearities can enrich the repertoire of dynamical phenomena and the emergence of complex structures.

The European Physics Journal Special Topics (EPJST) edition at hand, collects a series of articles reflecting recent advances in nonlinear dynamics and complex structures. Contributors to this issue are renowned specialists in a field belonging to nonlinear research and, in fact, some of the authors even established its foundations. While some contributions of this issue still tackle fundamental aspects of nonlinear dynamics, the majority of articles in this collection uses the arsenal of nonlinear methods to model questions belonging to a topical field. We tried to map this partition by sectioning the present edition.

A *first section* on *Fundamental Aspects of Nonlinear Dynamics* is opened by a mini-review by Lai and Grebogi [3] whose main purpose is to argue that quasiperiodicity just as random noise tends to suppress multistability. Through an analysis of quasiperiodically driven systems (damped pendulum and semi-conductor super lattice), the show that quasiperiodic driving indeed can eliminate multistability and generate robust chaos. Robust chaos, i.e.,the persistence of a chaotic attractor when

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control parameters are varied, is also in the focus of the review by Glendinning [4] who discusses different approaches to robust chaos and dwells on the extent to which the mechanisms of its generation are understood. As an outcome he provides a refinement of Young's Theorem and verifies its conditions numerically. The article by Rankin and Osinga [5] touches on the properties of periodic channels, i.e. multi-dimensional generalizations of periodic windows in a one-parameter bifurcation diagram, that occur in a locus of boundary crisis. Varying parameters of the Ikeda map the authors reconstruct geometric properties of periodic channels and neighboring chaotic attractors. Similar observations were reported for a three-parameter study of a quasi-periodically forced Hnon map, but are novel for two-dimensional maps. The article by Saiki *et al.* [6] draws a connection to the classical Lorenz equations by considering its embedding in a whole family of related differential equations. Restricting to a particular subclass for which trajectories stay on the three-sphere they find a surprisingly rich variety of dynamics hitherto unknown for Lorenz systems. Strange nonchaotic attractor (SNA) are addressed by the article of Doroshenko and Kuznetsov [7]. By mapping a specific system of ODEs to its corresponding Hunt and Ott map they can investigate a robust SNA system. Numerical results indicate that SNA indeed occurs and the authors confirm this finding by analysing the topological features of the map for related phase variables. A system exhibiting transient chaos is in the focus of the contribution by Felk *et al.* [8]. Here, transient chaos is constructed by two coupled twist maps with weak dissipation and is associated with a chaotic saddle situated near the resonance web of the Hamiltonian system and gets destroyed with increasing dissipation. Chaos control by feedback is well-known since long. In the paper by Arecchi *et al.* [9] an alternative scheme is discussed, the so-called phase control of chaos. In their contribution the authors investigate the application of square pulses to the paradigmatic driven Duffing oscillator with a focus on the question where to apply the control term to reach best efficiency and how effectiveness depends on the details of the duty cycle. The first section is completed by a research paper contributed by Politi *et al.* [10] in which the authors show if and how collective chaos, defined as irregular behavior on macroscopic scales, can emerge in mean-field coupled identical phase-oscillators. In the context of identical units they introduce a new way of representing the microscopic configurations which allows for a natural comparison between the microscopic and macroscopic regimes in terms of the range of finite perturbations. Most interestingly, this leads to the detection of a mesoscopic range where neither the microscopic nor the macroscopic rule applies.

The *second section* encompasses articles related to the topics of *Network Dynamics and Chimera States*. Hellen *et al.* [11] map genetic networks to electronic circuits with improved design which allows them to perform study the former through numerical simulations and mathematical analyses with the aim of precisely controlling the initial conditions when studying a multistable system like the quorum-sensing-coupled Repressilators. In this way they find coexistence of in-phase and anti-phase limit cycles, noise-induced transitions between these states, and the influence of high period limit cycles on the complex dynamics. In [12] Rubidio *et al.* present general solutions for current conservative DC/AC circuit networks with resistive, capacitive, and/or inductive edge characteristics, proposing an alternative to Kirchhoffs equations that is advantageous for constantly changing locations of inputs and outputs. Their novel approach provides a rigorous link between network topology and the steady-state currents of a conservative circuit network. An application of network dynamics on the global scale is shared by Brenner *et al.* [13] who use a complex network approach to model and analyse disease spreading dynamics. Their used SEIR compartmental model is indeed inspired by real world scenarios and via modulating the transmission rate by climatic factors they focus on aspects of climate change. In this way they find that spreading patterns of infectious diseases depend on both the network structure and the climatic setup of the environment. The next three articles are devoted to so-called chimera states, i.e. the robust coexistence of coherence and incoherence in networks of identical oscillators with non-local coupling. The contribution by Rybalova *et al.* [14] is inspired by the question how properties of individual ensemble elements can influence the appearance of chimera states. To solve this question the authors study coherenceincoherence transitions in ensembles of nonlocally coupled Henon and Lozi maps, describe their similarities and fundamental differences and find that completely synchronized chaos exists in both systems for dominant coupling, as does desynchronized spatio-temporal chaos for weak coupling. In [15] Maistrenko *et al.* study the effect of non-local coupling in three-dimensional networks of Kuramoto phase oscillators and investigate conditions for the emergence and stability of scroll wave chimeras. As a result of their demanding numerical simulations they find complex chimera states in 3-d (Hopf links and trefoils) that exist only for non-local coupling and sufficiently large phase shift between oscillators. The final paper in the second section by Sawicki *et al.* [16] dwells on the interplay of complex network topology and time delay influences chimera states and other complex spatio-temporal patterns. Studying a ring of N identical van der Pol oscillators with different coupling topologies the authors find that the interplay of complex hierarchical network topology and time delay results in a plethora of patterns going beyond regular two-population or nonlocally coupled ring networks. They thus provide evidence that time delay can play a key role for promotion or destruction of chimera patterns.

The *third sectio*n subsumes four articles under the section title *Synchronization*. The contribution by Banerjee *et al.* [17] explores the constructive role of heterogeneity for synchronization in chaotic Rssler oscillators using different coupling configurations (a one-dimensional open array, a star network, a ring of oscillators and a two-dimensional lattice of oscillators). Through numerical simulations they show that synchronization can be enhanced by an induced heterogeneity or a parameter mismatch in a suitably located central node works as a relaying device. Combined effects of conjugate coupling and time-delay in nonlinear oscillators are reported in the paper by Sharma *et al.* [18]; this setup is interesting for a coupling of dissimilar variables on its own mimics time delay coupling. For a paradigmatic limit cycle oscillator (Stuart-Landau) and an ecological model (enlarged Truscott-Brindley), and with coupling implemented through cross diffusion terms, they find that this coupling scheme can induce an anomalous transition from amplitude or oscillation death to a state of desynchronized motion, even for identical oscillators. Synchronization in network motifs of delay-coupled neurons is at the heart of an analysis contributed by Sausedo-Solorio and Pisarchik [19]. Through simulations of Rulkov neurons (2d-nonlinear map) the authors analyze how network motifs synchronize in the presence of a synaptic delay and a feedback loop and in particular how synchronization depends on the coupling strength and synaptic delay. The forth paper in this section by Goldobin *et al.* [20] provides a detailed study of competition of common noise and a desynchronizing global coupling of the Kuramoto-Sakaguchi type. The basic model is an ensemble of infinitely many phases and allows for a comprehensive analytical treatment via WatanabeStrogatz and OttAntonsen approaches. Most interesting effects appear when the noise and the coupling compete.

A *fourth section* collects articles that belong to the fields of *Neuronal Dynamics and Extreme Events in Excitable Systems*. In [21] Shaffer *et al.* investigate a tonic (rhythmic single spiking) to bursting (repeating sequences of multiple spikes) transition that in a linear chain of three synchronous model neurons (called triads) connected via electrical synapses. To this end they perform numerical simulations of three Huber-Braun model neurons, mimicking electrical synapses through additional ionic currents and show striking differences between the bifurcation scenarios in single neurons and in coupled chains triads. In their contribution Khamesian and Neiman

[22] study the deterministic and stochastic dynamics of a simple nonlinear model for the hair bundle of the bullfrog saccular hair cell including internal noise. Control parameters used in this study are the strength of fast adaptation and the membrane potential. Their results suggest that fast adaptation significantly affects the dynamics of the hair bundle. A description of neuronal networks in terms of scale-free networks of excitable systems (FitzHugh-Nagumo units) is underlying the article shared by Rings *et al.* [23] and in which they aim to clarify the role of high- and low -degree units in the generation of extreme events. Through their analysis they find that low-degree nodes trigger extremes via so-called proto-events while hubs propagate these to the initially inactive nodes. Extreme events are also in the focus of the contribution by Martinez Alvarez *et al.* [24], however, now with a focus on identifying early-warning signals of extreme events. Employing a method of ordinal statistics to local peaks of a time series generated by a model of laser dynamics they are able to detect ordinal patterns preceding extreme events. Being a proof of concept, the proposed method may be useful for other systems where extremes are generated by a mechanism that is dominated by a deterministic dynamics.

A *fifth section* collects research papers that may be titled *Fluctuations and Noise in Complex Systems.* In [25] Sprott *et al.* investigate a periodically forced chaotic system similar to the forced van der Pol oscillator but with a spatially-periodic damping (cosine term). What they find is a system with an infinite number of coexisting attractors, including limit cycles, attracting tori, and strange attractors, something they call megastability. A periodical forcing of the Brusselator in the low-frequency limit of the drive is investigated by Freire *et al.* [26]. A remarkable finding is that while this low-frequency limit is largely free of chaos it contains a dense net of oscillatory solutions whose waveforms comprise a number of spikes growing without bound as a function of the control parameters. Electrochemical oscillations on nanoscale electrodes are considered by Cosi and Krischer [27]. Of special interest is a comparison with chemical oscillations in small systems where molecular noise becomes important. Performing simulations of a prototypical potentiostatic oscillator that exhibits negative differential resistance they demonstrate peculiar features of electrochemical nanoscale oscillators that are linked to molecular noise. The role of nonlinearities for the conversion of chemical into other forms of energy (electrical or ecological) is investigated in a contribution by Ebeling and Feistel [28]. They aim at finding examples with high efficiency and, in this context, transfer the SET depot model to a fuel cell or predator prey dynamics. They find that high efficiency needs the exploitation of nonlinear effects and an optimization. In [29] Drotos *et al.* are concerned with climate dynamics and its strong internal variability. In the framework of a dynamical systems approach this suggests the notion of a chaotic attractor and in combination with climate change leads to the concept of a snapshot attractor, naturally arising in an ensemble description. Using an intermediate-complexity general circulation model (the Planet Simulator) they argue that it is important to check whether convergence to the attractor is reached. The final article in this fifth section by Milster *et al.* [30] presents a consistent procedure of adiabatic elimination of the orientational variable of a micro-swimmer which is an active Brownian particle moving at constant speed but with fluctuating orientation. Equations resulting via systematic elimination procedures, starting either form the Langevin equation or the related Fokker-Planck equation, still reflect important microscopic properties of the micro-swimmer as, for instance, the conservation of kinetic energy. Only after averaging over random orientations the particles loses this property and the description becomes similar to that of a normal overdamped Brownian particle.

In a *sixth section* we grouped four contributions that investigate *Dynamics in Flows.* In [31] Ser-Giacomi *et al.* elaborate on Lagrangian Flow Networks (LFNs). These arise in coarse-grained descriptions of a fluid dynamics where nodes correspond to small regions in the fluid domain and mass transfer between these regions define weighted links. Based on this method transfer, some properties of open flows as, for instance, escape rates are mapped to network measures. The authors illustrate this with a simple model system and confirm that the LFN approach is useful even for a description of open flows. Describing the advection of small inertial particles in different flow types naturally leads to the concept of the history force. In their contribution Guseva *et al.* [32] investigate the appearance of long transients in the presence of the history force. Using the so-called snapshot attractor approach enables exploitation of a time-scale separation, thus allowing them to identify a short-term exponential convergence and a long-term power law behavior. A description of the transport of inertial particles is also what Vilela and Oliveira [33] are concerned with. For inertial particles denser than the carrying flow (aerosols) the fluid flow can be effectively described by the so-called Stokes map. The authors dwell on the qualitatitve similarities between the dynamics given by the Maxey-Riley equation (for flows) and the Stokes map and show that gravity can be included in the description. The last article in the section on fluid dynamics is a paper by Dan *et al.* [34] who investigate the bursting dynamics in a Rayleigh-Bnard convection model when the Rayleigh-number is modulated slowly but periodically near the instabilities or the bifurcation points. Applying limits in the Boussinesq equations and performing bifurcation analysis the authors show that the quasi-static dynamical system exhibits a rich bifurcation pattern close to the onset of Rayleigh-Bénard convection in low Prandtl number fluids .

The final, *seventh section* comprises contributions that belong to the field of *Ecological Dynamics*. In [35] van Voorn and Kooi advocate a combination of bifurcation and sensitivity analyses in the study of ODE models. They exemplify their argument by applying the proposed approach to three representations of a predator-prey model thus showing its usefulness for model development and analysis. A sensitivity analysis is used by Chakraborty *et al.* [36] to study the role of agricultural impact on the formation of harmful algal blooms. Based on a six-component ODE model, through a qualitative analysis and numerical simulations, they investigate the role of a fertilizer input rate on different dynamical features of the system, thus tracing anthropogenic activities in the occurrence of algal blooms and dissolved oxygen levels. A better understanding of the role of motifs and their dynamical features in food web networks surely is beneficial and desirable. Karnatak and Wollrab [37] explore the dynamical consequences of a shift between two central tritrophic food web motifs, namely an intraguild predation (trophic interaction between natural antagonists) motif and a food chain. The draw interesting ecological conclusions from analysing a dynamical flow system in which they smoothly alter the interaction topology. It is widely recognized that space is an essential dimension for many ecological phenomena. Interacting ecological populations distributed in space are addressed by Arumugam *et al.* [38] with the objective to clarify the effect of species dispersal on a spatial ecological system consisting of heterogeneous fragmented habitats. Using a so-called meta-population model, in which fragmented habitats are connected by dispersal with mean-field diffusive coupling, they find that dispersal through mean-field coupling enhances the rhythmic oscillations and the synchrony-stability relationship. A spatial aspect is also behind the biological invasion modeled by Siekman *et al.* [39] using a spatio-temporal Lotka-Volterra model with non-standard nonlinear noise (saturating environmental noise intensity mimicking that individuals do not respond independently to environmental fluctuations). They examine in more detail the combined effect of Fokker-Planck diffusion and nonlinear noise and arrive at predictions different from those of standard models for environmental fluctuations. The final article of this section - and of this EPJST issue - is a report by Zelnik and Tzuk [40] who focus on wavelength selection beyond the Turing regime (where a uniform state is unstable to small non-uniform perturbations) in models of dryland ecosystems as a case study. The step beyond the Turing regime either by moving into bistable regions, and by considering the effect of disturbances that are not locally small, and therefore cannot be linearly approximated. Using simulations from three different models of dryland vegetation and analysing them they derive a relation between the wavelength of the highest growth mode and the so-called snaking wavelength.

This broad overview makes clear that elements of nonlinear dynamics, stochastic processes and complexity research have permeated many fields of applied science but that even today fundamental questions are still under investigation. A compilation of recent advances is indeed timely. However, since this edition is also a Festschrift on the occasion of Ulrike Feudel's 60th birthday we should not conceal that the circle of contributors to this edition also reflects long-term collaborators and scientific disciples of Ulrike Feudel. Her own contributions to the developing field of nonlinear science and to applications, especially in ecological research, are manifold and widely recognized - an appreciation of this is found in the opener of this edition [3] - and also reflected by the fact that many contributors in this issue directly reference her results. Almost everybody that we, the editors, asked was happily agreeing to share an article to this edition. The responsibility for inviting contributors is completely on the side of editors and we apologize to all those scientific colleagues that we missed and that deserved to be asked. We wish that this edition may serve the science community as a reference for the next few years and we dedicate it to Ulrike Feudel.

Happy Birthady Ulrike!

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