Introduction to focus issue: Recurrence quantification analysis for understanding complex systems

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Introduction to focus issue: Recurrence quantification analysis for understanding complex systems

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In 1987, recurrence plots were first introduced by Eckmann, Oliffson-Kamphorst, and Ruelle as a simple graphical tool to visualize basic dynamical characteristics of time series.[1] This present Focus Issue is dedicated to the 30th anniversary of recurrence plots and constitutes a unique collection of diverse papers on advanced recurrence plots, their extensions and ramifications, as well as their broad applications and utility. In the last three decades, an analytical framework based on recurrence plots has been developed, demonstrating an unanticipated but huge potential stemming from the original conceptualizations.[2,3] In its brief history, thousands of recurrence publications over numerous disciplines spanning these three decades have permeated the scientific literature. In addition, regular scientific meetings continue to attract and recruit new members to the "recurrence community" indicating lively growth and expansion into new disciplines of inquiry. For example, our most recent meeting in Brazil at the Escola Politénica Universidade De São Paulo (August 23–25, 2017) focused on disciplines of engineering, earth science, and life and social sciences.

A recurrence plot visualizes the times when the phase space trajectory of a dynamical system recurs to previous (or later) states up to a small error (the recurrence threshold).[1,2] The recurrence plot is the ground base for quantification of the recurrence structures, e.g., using recurrence quantification analysis[4] or recurrence networks.[5] Recurrence analysis of time series can be used to classify different signals or states, to identify transitions in the dynamics, or even to investigate interrelations, coupling directions, and synchronization between different time series.

A fundamental parameter in recurrence analysis is the recurrence threshold. When considering systems with changing dynamics, the threshold selection deserves special attention. Kraemer *et al*. discuss the effect of time-delay embedding and the consequences for threshold selection.[6] Prado *et al*. suggest an approach of optimizing the selection of the threshold in order to better find regime transitions in nonstationary systems or to infer coupling between dynamical systems.[7] As for any time series analysis, recurrence-based methods are also affected by certain challenges, such as noisy data or time series with irregular sampling. For the latter, Lekscha and Donner show how to use Legendre polynoms for reconstructing the phase space trajectory, which is then used for the recurrence analysis.[8] Wendi and Marwan reconsider an alternative criterion of recurrence[9] and extend it for noisy data; moreover, some of the basic elements of recurrence quantification analysis are redefined in order to overcome the challenges with noise.[10] Further challenges are related to special use cases, such as analyzing spatial data, event data, and discourses. These challenges are solved by a combination of complex networks and recurrences that allow for investigating spatial data,[11] introducing a new windowing concept for recurrence analysis,[12] and extending the conceptual recurrence quantification analysis for the discourse data.[13] All these new developments emphasize the applicability of the recurrence approach. The potentials of this approach are also best demonstrated by prototypical examples and selected physical problems. Ramdani *et al*. apply recurrence analysis to investigate the correlation structure of stochastic processes, such as fractional Gaussian noise;[14] Santos *et al*. study the regime changes in the standard nontwist map;[15] and Lameu *et al*. use recurrence analysis to identify chaotic burst phase synchronization in networks.[16] Moreover, recurrence plots contain enough information about time series that they can be used for nonparametric inferential statistics, as worked out by Wallot and Leonardi.[17]

The recurrence plot framework can be applied to diverse research questions in various scientific disciplines. The collection of studies in this Focus Issue gives an overview about this. By using recurrence quantification analysis as test statistics in surrogate data tests, the hypothesis that musical compositions arose from a Markov chain is tested.[18] Recurrence analysis is further used to identify events, regime transitions, and bifurcations, such as in social media streams (concept drifts in Twitter sentiments),[19] in the nonlinear magnetospheric dynamics of the earth's magnetosphere (magnetic storms),[20] in electrochemical systems (corrosion processes),[21] in the cardiovascular system to detect physiological stress,[22] and in polysomnography data for sleep-wake detection.[23] Applications of recurrence plots in medicine have a long tradition and were one of the drivers of certain developments, e.g., leading to the recurrence quantification analysis. Therefore, there is no surprise that recurrence plot methods are widely applied for different medical purposes: to identify certain physiological or pathological states, e.g., voice disorder,[24] atrial fibrillation,[25] or patients' response to ventilator treatment;[26] to analyze the quality of surgeons using dual eye tracking;[27] or to classify certain states, e.g., for an emotion recognition system,[28] or to distinguish between mental fatigue and normal mental state (interesting for brain-computer interfaces).[29] Further applications presented here and completing the disciplines refer to the detection of unstable periodic orbits in mineralizing geological systems[30] and to investigate the coupling between the Pacific and the tropical North Atlantic by an atmosphere-land bridge (via the Amazonian).[31] The diversity of topics in general and in this Focus Issue speaks to the wide applicability of recurrence plots across many disciplines of inquiry.

In summary, from their very outset 30 years ago, recurrence plots are not only beautiful to look at (art) but also contain hidden quantitative details that report on dynamical subtleties (science). The ability to embed vector inputs from the temporal and spatial domains into higher dimensional spaces teases out numerical descriptors that have amazing utility in diagnosing real-world dynamics. As evidenced by all the unique contributions to this Focus Issue, recurrence plots and their quantifications are powerful nonlinear tools whose applications run circles around classical linear methodologies. Researchers not familiar with recurrence plots are encouraged to apply this approach to their system of choice. The hope is that new generations of scientists will catch the vision and contribute creatively to the field. Indeed, there seems to be no limit to the type of dynamic that can be viewed from this perspective. In short, recurrence plots are here to stay. Indeed, we are all indebted to Eckmann, Oliffson-Kamphorst, and Ruelle for their astounding contribution and key insights from so many years ago.[1]

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