1 Handbook of Time Series Analysis: Introduction and Overview

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Mathematics, Physics, and Engineering are very successful in understanding phenomena of the natural world and building technology upon this based on the first principle modeling. However, for complex systems like those appearing in the fields of biology and medicine, this approach is not feasible and an understanding of the behavior can only be based upon the analysis of the measured data of the dynamics, the so-called time series.

Time series analysis has different roots in Mathematics, Physics, and Engineering. The approaches differ by their basic assumptions. While in Mathematics linear stochastic systems were one of the centers of interest, in Physics nonlinear deterministic systems were investigated. While the different strains of the methodological developments and concepts evolved independently in different disciplines for many years, during the past decade, enhanced cross-fertilization between the different disciplines took place, for instance, by the development of methods for nonlinear stochastic systems.

This handbook written by leading experts in their fields provides an up-to-date survey of current research topics and applications of time series analysis. It covers univariate as well as bivariate and multivariate time series analysis techniques. The latter came into the focus of research when recording devices enabled more-dimensional simultaneous recordings. Even though bivariate analysis is basically multivariate analysis, there are some phenomena which can occur only in three or more dimensions, for instance, indirect interdependences between two processes.

The aim of this handbook is to present both theoretical concepts of various analysis techniques and the application of these techniques to real-world data. The applications cover a large variety of research areas ranging from electronic circuits to human electroencephalography. The interplay between challenges posed by empirical data and the possibilities offered by new analysis methods has been proven to be successful and stimulating.

In the first chapter, Henry D. I. Abarbanel and Ulrich Parlitz present different approaches to nonlinear systems. By means of a real-world example of a recording from a single neuron, they discuss how to analyze these data. Concepts such as the Lyapunov exponent, i.e., a measure for chaos, prediction, and modeling in

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nonlinear systems, are introduced with a critical focus on their limitations. Ready to apply procedures are given allowing an immediate application to one's own data.

Local modeling is being dealt with by David Engster and Ulrich Parlitz. Local models are amongst the most precise methods for time series prediction. This chapter describes the basic parameters of local modeling. To show the efficiency of this procedure, several artificial and real-world data, for instance experimental friction data sets, are predicted using local models. As an alternative to strict local modeling, cluster weighted modeling is also discussed using an expectation-maximization (EM) algorithm as a parameter optimization procedure.

Holger Kantz and Eckehard Olbrich present concepts, methods, and algorithms for predicting time series from the knowledge of the past. Thereby, they especially concentrate on nonlinear stochastic processes which have to be dealt with by probabilistic predictions. They calculate a certain prediction range in which future values are going to fall. They complete their chapter by discussing verification techniques for their forecasted values, which is very important when dealing with real-world data.

Noise and randomness in biological systems have often been treated as an unwelcome byproduct. Patrick Celka and co-workers identify different noise sources and their impact on dynamical systems. This contribution discusses the concept of randomness and how to best access the information one wants to retrieve. Different time series analysis techniques are presented. The applications govern speech enhancement, evoked potentials, cardiovascular system, and brain–machine interface.

The chapter of Ursula Gather and co-workers is dedicated to robust filtering procedures for signal extraction from noisy time series. The authors present various filter techniques with their specific properties and extensions in order to process noisy data or data contaminated with outliers. They point to the variety of different approaches and compare the advantages and disadvantages. By means of simulated data they demonstrate the different conceptual properties.

Dealing with bivariate time series analysis techniques, the chapter of Michael Rosenblum and co-workers is dedicated to the phenomenon of phase synchronization and the detection of coupling in nonlinear dynamical systems. The authors discuss the usage of model-based and nonmodel-based techniques and introduce novel ideas to detect weak interactions between two processes, together with the corresponding strength and direction of interactions. They illustrate their analysis techniques by application to data characterizing the cardiorespiratory interaction.

An approach to detect directional coupling between oscillatory systems from short time series based on empirical modeling of their phase dynamics is introduced by Dmitry Smirnov and Boris Petrovich Bezruchko. This time series analysis technique is utilized to analyze electroencephalography recordings with the purpose of epileptic focus localization and climatic data representing the dynamics of the North Atlantic Oscillation and El Niño/Southern Oscillation processes.

Phase synchronization analysis of brain signals, for instance intracranial electroencephalography data recorded from epilepsy patients, has come into the focus of neuroscience research. Mario Chavez and co-workers suggest a data-driven time series analysis technique to select the important contents in a signal with multiple frequencies, the empirical mode decomposition. They summarize this concept and demonstrate its applicability to model systems and apply it to the analysis of human epilepsy data.

For cases where the definition of the phase used by common approaches is impossible, Mamen Romano and co-workers present a way to detect and quantify phase synchronization using the concept of recurrences. Furthermore, to test for phase synchronization, an algorithm to generate surrogate time series based on recurrences is discussed. An application to fixational eye movement data complements the results for model systems.

Theoden I. Netoff and co-workers dedicated their work to infer coupling and interaction in weakly coupled systems, especially in the presence of noise and nonlinearity. To this end, they applied several analysis techniques to model data and to data obtained from an electronic circuit. They explored advantages and disadvantages of the methods in specific cases. The conclusion of their chapter is that nonlinear methods are more sensitive to detect coupling under ideal conditions. However, in the presence of noise, linear techniques are more robust.

Dealing with multivariate systems, the chapter of Manfred Deistler is dedicated to state space and autoregressive moving average models. He summarizes the basic ideas about state space models and autoregressive moving average models including external influence. He focuses on the mathematics and discusses approaches to parameter estimation. Lower dimensional parameterizations of these state space models are described to cope with high-dimensional time series.

David S. Stoffer and Myron J. Katzoff introduce an extension to spatio-temporal state space models. They concentrate on the concept of spatially constrained state-space models presenting ideas and mathematical aspects. Their application is dedicated to real-time disease surveillance by analyzing weekly influenza and pneumonia mortality collected in the northeastern United States that is essential in helping to detect the presence of a disease outbreak and in supporting the characterization of that outbreak by public health officials.

Graphical models are introduced in the chapter by Michael Eichler. He introduces the mathematical basis for a graphical representation of the interaction schemes obtained by multivariate analysis techniques. Moreover, the inference in these graphs is discussed and illustrated by means of model systems. Novel multivariate analysis techniques that allow distinction not only of direct and indirect interactions but also of the direction of interactions leading to such graphs are summarized and applied to neurophysiological and fMRI data.

The directed transfer function allows detection of directed influences in multivariate systems. Katarzyna J. Blinowska and Maciej Kamiñski introduce the directed transfer function, extend the concept to nonstationary data, and discuss approaches to decide its statistical significance. In their application, they analyze human electroencephalography data using the directed transfer function. They complement this work by comparisons of different multivariate analysis techniques.

Luiz A. Baccalá and co-workers are working on a multivariate analysis technique called partial directed coherence. Besides several applications of this technique, one of the challenges when applying this technique to real-world data is that a significance level is mandatory. Several approaches to evaluate statistical significance in practice are presented and discussed in their chapter. Moreover, they compare their technique to other techniques suggested for a similar purpose. The techniques are applied to electroencephalography data during and immediately before an epileptic seizure.

Another multivariate analysis technique to detect the directions of interactions between processes is discussed by Mingzhou Ding and co-workers. Bivariate Granger causality and conditional Granger causality are presented with particular emphasis on their spectral representations. Following a discussion of the theoretical properties and characteristics, the time series analysis technique is applied to model systems and to multichannel local field potentials recorded from monkeys performing a visuomotor task.

Pedro A. Valdés-Sosa and co-workers focus in their chapter on multivariate autoregressive models (MAR) based on a Bayesian formulation that combines several components of different types of penalizations as well as spatial *a priori* covariance matrices. This approach is shown to be practical by simulations and an application to concurrent EEG and fMRI time series gathered in order to analyze the origin of resting brain rhythms.

Ranging from univariate to multivariate analysis techniques, ranging from applications of physics to life sciences, covering an exceptionally broad spectrum of topics, beginners, experts as well as practitioners in linear and nonlinear time series analysis who seek to understand the actual developments will take advantage of this handbook.