Nonlinear Techniques for Signals Characterization

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INTRODUCTION

The field of nonlinear **signal characterization** and nonlinear signal processing has attracted a growing number of researchers in the past three decades. This comes from the fact that linear techniques have some limitations in certain areas of signal processing. Numerous nonlinear techniques have been introduced to complement the classical linear methods and as an alternative when the assumption of linearity is inappropriate. Two of these techniques are higher order statistics (HOS) and nonlinear dynamics theory (chaos). They have been widely applied to time series characterization and analysis in several fields, especially in biomedical signals.

Both HOS and chaos techniques have had a similar evolution. They were first studied around 1900: the method of moments (related to HOS) was developed by Pearson and in 1890 Henri Poincaré found sensitive dependence on initial conditions (a symptom of chaos) in a particular case of the three-body problem. Both approaches were replaced by linear techniques until around 1960, when Lorenz rediscovered by coincidence a chaotic system while he was studying the behaviour of air masses. Meanwhile, a group of statisticians at the University of California began to explore the use of HOS techniques again.

However, these techniques were ignored until 1980 when Mendel (Mendel, 1991) developed system identification techniques based on HOS and Ruelle (Ruelle, 1979), Packard (Packard, 1980), Takens (Takens, 1981) and Casdagli (Casdagli, 1989) set the methods to model nonlinear time series through chaos theory. But it is only recently that the application of HOS and chaos in time series has been feasible thanks to higher computation capacity of computers and Digital Signal Processing (DSP) technology.

The present article presents the state of the art of two nonlinear techniques applied to time series analysis: higher order statistics and chaos theory. Some measurements based on HOS and chaos techniques will be described and the way in which these measurements characterize different behaviours of a signal will be analized. The application of nonlinear measurements permits more realistic characterization of signals and therefore it is an advance in automatic systems development.

BACKGROUND

In digital signal processing, **estimators** are used in order to characterize signals and systems. These estimators are usually obtained using linear techniques. Their mathematical simplicity and the existence of a unifying linear systems theory made their computation easy. Furthermore, linear processing techniques offer satisfactory performance for a variety of applications.

However, linear models and techniques cannot solve issues such as nonlinearities due to noise, to the production system of the signal, system nonlinearities in digital signal acquisition, transmission and perception, nonlinearities introduced by the processing method and nonlinear dynamics behaviour. Therefore, the application of linear processing techniques leads to less realistic characterization of certain systems and signals. As a result of the shortcomings of linear techniques, analysis procedures are being revised and nonlinear techniques are being applied in computing **estimators** and models and in **signal characterization** to increase the possibilities of digital signal processing.

HOS is a field of statistical signal processing which has become very popular in the last 25 years. To date almost all digital signal processing have been based

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on second order statistics (autocorrelation function, power spectrum). HOS use extra information which can be used to get better estimates of noisy situation and nonlinearities.

Chaos theory (nonlinear dynamical theory) is a long-term unpredictable behaviour in a nonlinear dynamic system caused by sensitive on initial conditions. Therefore, irregularities in a signal can be produced not only by random external input but also by chaotic behaviour.

Both nonlinear techniques have been used in signals characterization and numerous automatic classification systems have been developed using HOS and chaos features in many fields. Texture classification (Coroyer, Declercq, Duvaut, 1997), seismic event prediction (Van Zyl, 2001), fault diagnosis in machine condition monitoring through vibration signals (Samanta, Al.Balushi. & Al-Araimi, 2006), (Wang & Lin, 2003) and economy (Hommes & Manzan, 2006) are some examples.

Their application in biomedical signals is especially important. Nonlinear features have proven to be useful in voice, electrocardiogram (ECG) and electroencephalogram (EEG) signals characterization. Automatic classification systems between pathological and healthy voices have been implemented using nonlinear features (Alonso, de León, Alonso, Ferrer, 2001) (Alonso, Díaz-de-María, Travieso, Ferrer, 2005). Nonlinear characteristics have been used in the detection of electrocardiographic changes through ECG signal (Ubeyli & Guler, 2004), in the evaluation of neurological diseases using EEG signal (Gulera, Ubeylib & Guler, 2005), (Kannathal, Lim Choo Min, Rajendra Acharya & Sadasivan, 2005) and in diagnosis of phonocardiogram (Shen, Shen, 1997).

NONLINEAR METHODS: CHAOS THEORY AND HIGHER ORDER STATISTICS APPLIED TO TIME SERIES

Higher Order Statistics

Higher Order Statistics, known as cumulants and their Fourier transform, known as polyspectra are extensions of second-order measures (such as the autocorrelation function and power spectrum). Some advantages of HOS over second-order statistics are:

1. HOS give amplitude and phase information in the spectral domain, whereas second order statistics only give amplitude information (Mendel, 1991) (Nikias & Petropulu, 1993). Therefore, non-minimum phase signals and certain types of phase coupling (associated with nonlinearities) cannot be correctly identified by second-order statistics.
2. HOS are blind to Gaussian processes whereas correlation is not (Mendel, 1991). Therefore, cumulants can be used in determining Gaussian noise levels in a signal, separating non-Gaussian signals from Gaussian noise, in harmonics components estimation or in increasing signal to noise ratio (SNR) when signals are contaminated with Gaussian noise.

The second-order measures work properly if the signal has a Gaussian probability density function, but many real-life signals are non-Gaussian. Therefore, HOS are a powerful tool to work with non-Gaussian and nonlinear processes.

Next, some higher order statistics measurements are shown and their usefulness in characterizing certain nonlinear phenomena is explained.

Third Order Moment: Skewness

Skewness is a third order moment and a measure of the asymmetry in a probability distribution. This measurement enables us to discriminate among different kind of data distribution as its value varies according to the asymmetry of a distribution. The skewness of a Normal distribution is zero (data symmetric about the mean), positive skewness corresponds to a distribution with a right tail longer and negative skewness to a distribution with a left tail longer.

In most cases normal distribution is assumed, but data points are not usually perfectly symmetric. Skewness reflects positive or negative deviations from the mean and gives more realistic characterization of a data set.

Fourth Order Moment: Kurtosis

Kurtosis is a fourth order moment and a measure of whether the data in a probability distribution are peaked

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