Neurocomputing 179 (2016) 264–282

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

A tutorial on signal energy and its applications

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ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form
2 December 2015
Accepted 7 December 2015
Communicated by Hu Jun
Available online 17 December 2015

Keywords:
Signal energy
Pattern recognition
Feature extraction
Neurophysiological signal processing
Speech processing
Image processing

ABSTRACT

This tutorial, dedicated both to young professionals and students working with digital signal processing and pattern recognition, introduces three feature extraction approaches based on signal energy, characterising alternative and innovative ways for its use. The proposed theory, smoothly presented, is complemented with numerical examples, source-codes in C/C++ programming language, and applications in a diversity of computational problems, namely, neurophysiological signal processing, speech processing, and image processing. The lack of novelty in current energy-based approaches and the feasibility of a balance among *creativity*, *simplicity*, and *accuracy* constitutes the motivation for this text, which reveals how relevant the concept of signal energy may be, if properly employed.

1. Introduction

1.1. Motivation and tutorial structure

I have taught digital signal processing (DSP) and pattern recognition (PR) for almost twenty years, the period for which I have collected impressions from my undergraduate and graduate students of Computer Science, Electrical Engineering, and Applied Physics and Mathematics. This scenario I have been absorbed into, and mused on, inside which I have seen traditional concepts permanently being used without novelty, has motivated me to write this tutorial. Particularly, my intention is to show alternative and innovative ways to work with the concept of signal energy [1], improving its current usage as a feature extraction tool in benefit of DSP systems designed for PR [2,3]. I am absolutely sure that the aforementioned audience, for whom I dedicate this material, will take considerable advantage, not only of the concepts I present, but also of the tips and tricks shown, which provide a balance among *creativity*, *simplicity* and *accuracy*.

I have spent a considerable time to polish this text in order to offer the readers a smoothly written tutorial. Neither obscure equations nor algorithms with high orders of time and space complexity [4] can be found in the material I present. Instead, the mission of my essay, replete of explanations, figures, and source-codes in C/C++ programming language [5], is clarification. It innovates feature extraction based on signal energy, suggesting possible future trends. For that, it is organised as follows. The subject in study is presented in the next subsection of these introductory notes. Then, Section 2 describes the proposed approaches, Section 3 shows numerical examples, and Section 4 reports the tests and results obtained during the analyses of different types of signals. Lastly, Section 5 presents the conclusions.

Throughout the text, the reader will be able to understand that feature extraction, specially based on signal energy, plays an important role as being a methodology which aims to address real world complexities and improve real-life classification schemes, i.e., the ones which lead to uncertainty and partial truth, achieving tractability, robustness and low solution costs [6–22].

1.2. Problem statement and review

DSP systems designed for PR are characterised as being pattern-matching [23–26] or knowledge-based [27–32] approaches. In the former case, one or more template models derived from sample data are initially established in order to represent each class of interest.

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http://dx.doi.org/10.1016/j.neucom.2015.12.012
0925-2312/

Then, the classification of an unlabelled unidimensional (1D) digital signal, $s[\cdot]$, or a bidimensional (2D) digital signal, $m[\cdot][\cdot]$, is based on comparisons between the models and the input signal. The best match represents the class to which $s[\cdot]$, or $m[\cdot][\cdot]$, is assigned. In the latter case, one or more classifiers are trained in advance to identify $s[\cdot]$, or $m[\cdot][\cdot]$, as being a member of one or more specific classes, by means of statistical, numerical or optimisation-oriented approaches. Most of the times, the training procedures are based on sample data. Additionally, current literature describes some recent PR algorithms that combine pattern-matching and knowledge-based approaches. Classical examples of pattern-matching classifiers are Hard Thresholds (HTs), Distance Measures (DMs) and Correlation Coefficients (Rs). In contrast, Bayesian Modelling (BM), Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) represent knowledge-based approaches.

Disregarding the above-mentioned characterisation, and independent of the task carried out herein, i.e., template modelling, system training, signal assignment or identification, one restriction exists: neither $s[\cdot]$ nor $m[\cdot][\cdot]$ should be *directly* compared to the models or evaluated by the classifier. The reasons for that are their *relevant* and, most of the times, *variable* lengths, increasing computational costs and preventing the use of DMs, ANNs, or SVMs, that are only capable to lead with signals of predetermined dimensions. Furthermore, important information for classification may be hidden in the raw, or noisy, data. Therefore, an intermediary stage that converts digital signals of relevant and variable lengths to important information of reduced and predefined lengths, which are called feature vectors [33], is always required. This idea is shown in Fig. 1, being obvious that the feature-extraction step consists of a lossy procedure because, as mentioned above, it considerably reduces the dimension of the input signal. The direct consequence is that, the more the features preserve the information of interest from the signal under analysis, the more accurate the results of classification are.

Current literature teaches us that there are, basically, two different approaches for choosing features: *feature-learning* and *handcraft selection*. The former, outside the scope of this text, gathers a set of sophisticated techniques that learn the features automatically, forgoing human intervention [34]. Deep learning [35] is one classical example. On the other hand, in the latter, the system engineer is required to select the ideal features among many possibilities [2,3,36–46], being the signal energy, defined as

$$E(s[\cdot]) = \sum_{i=0}^{M-1} (s_i)^2, \tag{1}$$

with M representing the width, i.e., the length, of $s[\cdot]$, the simplest and most common one. Eq. (1) is adopted for 1D signals, however, in case of 2D signals, the definition becomes

$$E(m[\cdot][\cdot]) = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (m_{i,j})^2, \tag{2}$$

being N and M, respectively, the height and the width of $m[\cdot][\cdot]$.

Physically, the energy of a signal represents its capacity to perform work [47]. Particularly, if a speech signal is considered, its energy describes the work the speaker's lungs and vocal tract performed, as a function of time, to produce sound [48]. On the other hand, if an electrocardiogram (ECG) signal is under analysis, its energy consists of the effort the subject's heart required to pump blood, as a function of time [49]. Assuming that an image, for instance, its energy along the space expresses the corresponding penetrating intensity of its colours [50], and so on. Much research, well represented by the ones that are published in [6–8,51–53], describe the use of signal energy in different applications.

Time and frequency decompositions are commonly used to extract energy-based features from different types of signals, such as biological ones. In [54], a novel energy-based diagnostic distortion measure is proposed to assess the reconstructed signal quality of ECG compression algorithms. Similarly, the authors of the paper [55] analyse ECG beats, from an energy point-of-view, by accounting for the features derived from non-linear component in time and frequency domains using an energy operator. An energy-efficient design for ECG R-peak detection is the objective of the article [56]. Energy features of electroencephalogram (EEG) signals are used for classification in the paper [57], while digital identification of normal and alcoholic EEG signals, based on energy, is explored in [58]. In [59], the authors detect artifacts from high energy bursts in neonatal EEG. On the other hand, energy demands of diverse spiking cells from the neocortex, hippocampus, and thalamus are explored in [60].

In the scope of image processing, we also have many applications of signal energy. The paper [61] is dedicated to the extraction of energy-based features in handwritten Chinese documents. In the paper [62], handwritten character recognition is performed by using energy, as the main feature, in association with an extreme learning machine. The authors of the paper [63] perform handwritten documents text-line segmentation based on energy. Active contours driven by local likelihood image fitting energy are used for image segmentation in the paper [64]. Energy-efficient low bit rate image compression is the focus of the paper [65], while the paper [66] describes an algorithm for dense depth image synthesis via energy minimization. A new multi-focus image fusion algorithm based on energy is the objective of the paper [67].

Speech and music processing is another field in which signal energy plays an important role. The paper [68] explores online speech and music segmentation on its basis, while energy-based speech enhancement for hands-free communication is discussed in [69]. In the paper [70], a monaural speech and music source separation scheme, using discrete energy separation algorithm, is proposed. The effects of energy on robust speech recognition is studied in [71]. On the other hand, a study on the consistency analysis of energy parameter for Mandarin speech recognition is described in [72]. The paper [73] discusses voiced/non-voiced detection in noisy speech signals based on energy, while an energy-efficient spike encoding circuit for speech edge detection is the topic of the paper [74]. The enhancement of noisy speech, based on its energy, is studied in the paper [75]. Additionally, the paper [76] introduces energy-based blind separating algorithms

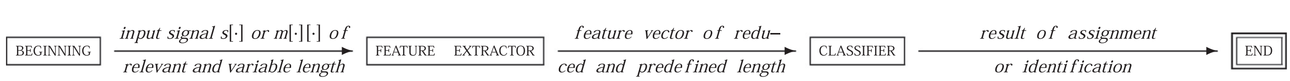

Fig. 1. Usual classification scheme for modern pattern-matching, knowledge-based, and combined approaches.