Applied Soft Computing 27 (2015) 590–601

Contents lists available at ScienceDirect

Applied Soft Computing

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

Signal processing and time series description: A Perspective of Computational Intelligence and Granular Computing

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ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form 5 June 2014
Accepted 10 June 2014
Available online 28 June 2014

Keywords:
Computational Intelligence
Biomedical signals
Neurocomputing
Fuzzy sets
Information granules
Granular Computing

ABSTRACT

This study provides a general introduction to the principles, algorithms and practice of Computational Intelligence (CI) and elaborates on their use to signal processing and time series. In this setting, we discuss the main technologies of Computational Intelligence (namely, neural networks, fuzzy sets or Granular Computing, and evolutionary optimization), identify their focal points and stress an overall synergistic character, which ultimately gives rise to the highly synergistic CI environment. Furthermore, the main advantages and limitations of the CI technologies are discussed. In the sequel, we present CI-oriented constructs in signal modeling, classification, and interpretation.

1. Introduction

There have been a significant number of various information technologies applied to biomedical signal analysis, interpretation, and classification. Along with the steady progress of hardware, new more advanced algorithmic developments have been reported upon. There are strong motivating factors and several compelling reasons behind this progress, which mainly results from the exposure to the challenges inherently associated with the domain of signal processing, analysis, and interpretation:

- Biomedical signals are one of the most important sources of diagnostic information. Their proper acquisition and processing provide an indispensible vehicle to support medical diagnosis. Acquired signals are affected by noise and their further processing calls for the use of advanced filtering techniques.
- A description and classification of signals call for nonlinear mechanisms producing a suitable set of features (descriptors) of the signal so that the ensuing classifiers come with significant discriminatory capabilities. We witness a great deal of various ways used in signal description being followed by a numerous classifiers.
- It is anticipated that any advanced computerized interpretation of signals has to be user-friendly, meaning that the results of classification/interpretation could be easily comprehended by a human user and any queries along the "what-if" investigations could be fully attended to. Likewise it becomes highly beneficial to endow the results of classification or prediction with confidence levels, expressed either numerically or linguistically. This requirement calls for an effective way of dealing with knowledge acquisition and knowledge processing when working with numeric signals.

Quite often these problems are intertwined and need to be dealt with in a holistic manner. We notice that some of them (preprocessing, filtering) require advanced nonlinear processing techniques while the others (interpretation) call for knowledge-oriented techniques. Altogether, a comprehensive methodological and algorithmic environment, which is offered by Computational Intelligence, comes as a viable alternative.

In this study, we discuss the main conceptual, methodological and algorithmic pillars of Computational Intelligence (CI), identify their main features and elaborate on their role in biomedical signal processing. To a significant extent, the content of this study is self-contained and the most essential ideas are elaborated on from scratch. The reader can benefit from some introductory knowledge of the subject matter on neural networks, fuzzy sets and evolutionary computing; see, for instance [30,31]. The presentation is provided in a top-down approach. We start with a concise

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http://dx.doi.org/10.1016/j.asoc.2014.06.030
1568-4946/

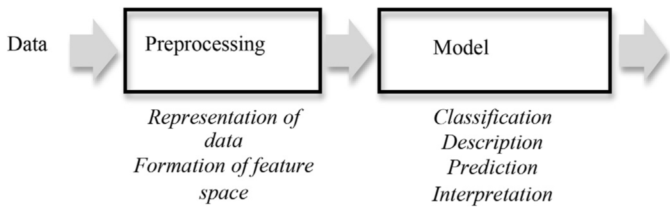

Fig. 1. An overall framework of signal analysis, processing, interpretation, prediction, and classification.

introduction to Computational Intelligence (CI) viewed as a highly synergistic environment bringing a number of highly visible technologies of Granular Computing, neural networks, and evolutionary optimization (Section 2). In a sequence of sections, Sections 3–5, we discuss neurocomputing, evolutionary optimization, and Granular Computing. Furthermore we show that the three main technologies of CI are naturally inclined to form useful synergistic linkages. Formal platforms of information granularity are discussed in Section 6. Practical insights identifying advantages and possible limitations of these technologies are carefully addressed. We elaborate on information granularity and its role in signal representation in Section 7. The concept of information granulation–degranulation is discussed in Section 8. The design of information granules regarded as semantically sound abstractions is covered in Sections 9 and 10. Here we discuss ways where not only numeric data – experimental evidence is taken into account but various tidbits of domain knowledge are also used in the formation of information granules. Ways of building information granules of higher type and higher order are discussed in Section 11. In Section 12, we relate key aspects of information granularity with time series and offer a hierarchical architecture supporting a realization of description and prediction tasks.

Fig. 1 shows a general scheme of processing (classification, description, prediction, etc.) with several with well-identified key modules; in the subsequent discussion we will be associating their realization in the setting of the fundamental technologies of Computational Intelligence. As far as the notation used in this study is concerned we follow the symbols being in common usage. Patterns (data) $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N$ are treated as vectors located in n-dimensional space $\mathbf{R}^n$, $||.||$ is used to denote a distance (Euclidean, Mahalanobis, Hamming, Tchebyshev, etc.). Fuzzy sets will be described by capital letters; the same notation is being used for their membership functions.

2. Computational Intelligence: an agenda of synergy of algorithms of learning, optimization and knowledge representation

Computational Intelligence can be defined in many different ways. Let us start by recalling two definitions or descriptions, which are commonly encountered in the literature

A system is computationally intelligent when it: deals with only numerical (low-level) data, has pattern recognition components, does not use knowledge in the AI sense; and additionally when it (begins to) exhibit (1) computational adaptivity; (2) computational fault tolerance, (3) speed approaching human-like turnaround, and (4) error rates that approximate human performance [6,7]

The description provided by W. Karplus comes as follows

CI substitutes intensive computation for insight how the system works. Neural networks, fuzzy systems and evolutionary Computation were all shunned by classical system and control theorists. CI umbrellas and unifies these and other revolutionary methods

The first description captures the essence of the area. Perhaps today such a definition becomes slightly extended by allowing for some new trends and technologies, which are visible in the design of intelligent systems. Nevertheless the essence of CI is well-captured.

The comprehensive monograph on CI [31] emphasizes the importance of synergy of the contributing and very much complementary technologies of fuzzy sets, neurocomputing and evolutionary optimization. In a nutshell, CI is about effective and omnipresent mechanisms of synergy exploited in a variety of tasks of analysis and design of intelligent systems. The reader may refer to [9,19], including fuzzy automata [23], which serve as comprehensive sources of updated material on CI. Some interesting more detailed studies visualizing a role of CI and showing how the optimization mechanisms (including Particle Swarm Optimization) are effectively utilized in the design of advanced models are reported [34–36,38].

In signal processing, especially, with regard to ECG signal processing and interpretation, the reader is referred to [1,10,11,17].

The emergence of CI is justifiable, and in some sense, unavoidable. Over time, being faced with more advanced problems, increased dimensionality and complexity of systems one has to deal with, neural networks, fuzzy sets and evolutionary computing started to exhibit some clear limitations. This is not startling at all as their research agendas are very much distinct and they focus on different aspects of the design of intelligent systems. The synergistic environment, in which the key pursuits of knowledge representation, learning and global optimization go hand in hand, becomes highly desirable.

Let us elaborate in more detail on knowledge representation as being captured by fuzzy sets. Fuzzy sets offer a unique and general opportunity to look at information granules as semantically meaningful entities endowed with detailed numeric description. For instance, consider an information granule termed *high* amplitude of signal. On the one hand, *high* is just a single symbol and as such could be processed at the level of symbolic processing encountered in Artificial Intelligence (AI). For instance, it could be one of the symbols used in syntactic pattern classifier captured by a collection of syntactic production rules or automata. On the other hand, the same granular entity *high* is associated with the detailed numeric description, which calibrates the concept in presence of available numeric evidence. A suitable level of abstraction helps us establish the most promising tradeoff between detailed and abstract view at the problem/data. Of course, the choice of the tradeoff is problem driven and depends upon the task and the main objectives specified therein. Likewise, the same information granule *high* can be looked at in less detail and through the use of some partially specified numeric content (that is in the form of higher type information granules, say fuzzy sets of type-2) could be processed in a semi-numeric fashion. In this way, the granularity of information and a formal mechanism used in granulation itself offers a way to position anywhere in-between symbolic view and numeric perception or quantification of the reality.

One may emphasize an important and enlightening linkage between Computational Intelligence and Artificial Intelligence (AI). To a significant extent, AI is a synonym of symbol-driven processing faculty. CI effectively exploits numeric data however owing to the technology of Granular Computing, it may invoke computing based on information described at various levels of granularity by inherently associating such granules with their underlying semantics described in a numeric or semi-numeric fashion (such as e.g., membership functions, characteristic functions or interval-valued mappings). The granularity of results supports the user-friendly nature of CI models. They can also form an important construct to be further used in facilitating interaction with the user as well as forming linkages with symbolic processing of AI constructs. The