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ZCR-aided neurocomputing: A study with applications

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A B S T R A C T

This paper covers a particular area of interest in pattern recognition and knowledge-based systems (PRKbS), being intended for both young researchers and academic professionals who are looking for a polished and refined material. Its aim, playing the role of a tutorial that introduces three feature extraction (FE) approaches based on zero-crossing rates (ZCRs), is to offer cutting-edge algorithms in which clarity and creativity are predominant. The theory, smoothly shown and accompanied by numerical examples, innovatively characterises ZCRs as being neurocomputing agents. Source-codes in C/C++ programming language and interesting applications on speech segmentation, image border extraction and biomedical signal analysis complement the text.

1. Introduction

1.1. Objective and tutorial structure

In a previous work, I published a tutorial on signal energy and its applications [1], introducing alternative and innovative digital signal processing (DSP) algorithms designed for feature extraction (FE) [2–4] in pattern recognition and knowledge-based systems (PRKbS) [5,6]. At that time, I intended to cover the lack of novelty in related approaches based on consistency among *creativity, simplicity* and *accuracy*. So it is presently, opportunity in which three methods for FE from unidimensional (1D) and bidimensional (2D) data are defined, explained and exemplified, pursuing and taking advantage of my own three previous formulations [1]. The differences between that and this work are related to the concepts and their corresponding physical meanings adopted to substantiate them: antecedently, signal energy was used to provide information on workload, on the other hand, zero-crossing rates (ZCRs) are currently handled to retrieve spectral behaviour [7] of signals. Complementarily, ZCRs are interpreted as being neurocomputing agents, which characterises an innovation that this work offers to the scientific community. Another remarkable contribution consists of the use of ZCRs for 2D signal processing and pattern recognition, a concept practically inexistent up to date.

As in the previous, this essay suggests possible future trends for the PRKbS community. In doing so, it is organised as follows. The concept of ZCRs and some recent related work pertaining to these constitute the next subsections of these introductory notes. Then, Section 2 presents the proposed algorithms for FE, their corresponding implementations in C/C++ programming language [8] and my particular point-of-view which characterises ZCRs as being neurocomputing agents. Moving forward, Section 3 shows numerical examples and Section 4 describes the tests and results obtained during the analyses of both 1D and 2D data. Lastly, Section 5 reports the conclusions that are followed by the references.

Throughout this document, detailed descriptions, graphics, tables and algorithms are abundant, however, for a much better understanding, I strongly encourage you, the reader of this tutorial, to learn my previous text [1] before proceeding any further.

1.2. A review on ZCRs and their applications

Although its roots were traced back before [9] and throughout [10,11] the beginning of DSP, the suitability of ZCRs has been intensively pointed out by the speech processing community, the one in which their applications are more frequent [12]. Thus, ZCRs, as being the simplest existing tools used to extract basic spectral information from time-domain signals without their explicit conversion to the frequency-domain [13], play an important role in DSP and PRKbS.

Despite the word *rate* in its name, ZCR is defined, in its elementary form, as being the number of times a signal waveform

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0950-7051/

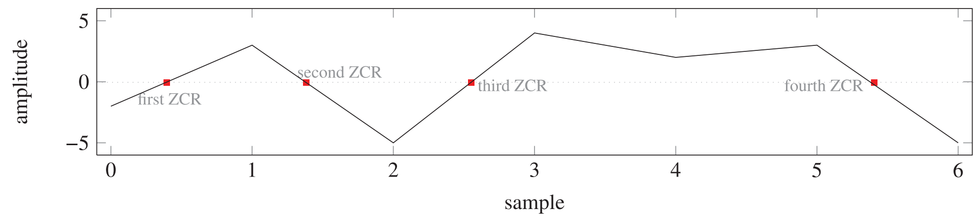

Fig. 1. The example signal $s[\cdot] = \{-2, 3, -5, 4, 2, 3, -5\}$ and its four zero-crossings represented as red square dots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

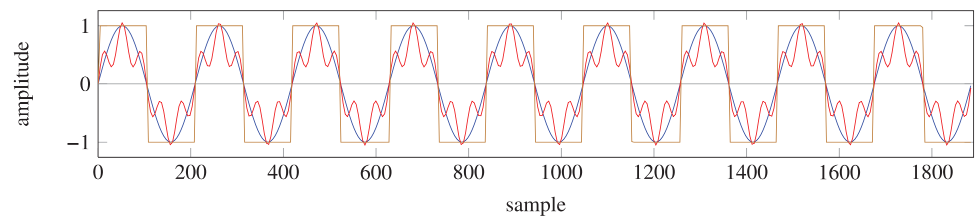

Fig. 2. In blue, the pure sine wave; in red, the composed sine wave; in brown, the square wave. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

crosses the amplitude zero. An alternative and formal manner to express this concept, letting $s[\cdot] = \{s_0, s_1, s_2, ..., s_{M-1}\}$ be a discrete-time signal of length $M > 1$, is

$$\text{ZCR}(s[\cdot]) = \frac{1}{2}\sum_{j=0}^{M-2} |sign(s_j) - sign(s_{j+1})|, \tag{1}$$

being $ZCR(s[\cdot]) \geq 0$ for any $s[\cdot]$ and $sign(x) = \begin{cases} 1 & \text{if } x \geqslant 0; \\ -1 & \text{otherwise} \end{cases}$. In the next section, distinct normalisation procedures will be applied to ZCRs in order for the word *rate* to make the intended sense.

As an example, let $s[\cdot]$, of size $M = 7$, be the discrete-time signal for which the samples are $\{-2, 3, -5, 4, 2, 3, -5\}$. Then, $\text{ZCR}(s[\cdot]) = \frac{1}{2}\sum_{j=0}^{M-2} |sign(s_j) - sign(s_{j+1})| = \frac{1}{2}\sum_{j=0}^{5} |sign(s_j) - sign(s_{j+1})| = \frac{1}{2}(|-1-1| + |1-(-1)| + |-1-1| + |1-1| + |1-1| + |1-(-1)|) = \frac{1}{2}(|-2| + |2| + |-2| + |0| + |0| + |2|) = \frac{1}{2}(2+2+2+0+0+2) = 4$, i.e., the waveform of $s[\cdot]$ crosses its amplitude axis four times at the value 0, as can be easily seen in Fig. 1.

The elementary example I have just described is really quite simple, however, I ask for your attention in order to figure out the correct physical meaning of ZCRs, avoiding underestimations. For that, a basic input drawn from Fourier's theory and his mathematical series [14] is required: the statement which confirms that any signal waveform distinct of the sinusoidal can be decomposed as an infinite linear combination of sinusoids with multiple frequencies, called *harmonics*. Thus, a signal waveform that matches *exactly* a sinusoidal function, with a certain period, phase and amplitude, is classified as being *pure*. Conversely, any other type of signal waveform consists of a main sinusoid called *fundamental* or *first harmonic*, owning the lowest frequency among the set, added together with the other sinusoids of higher frequencies, i.e., the second harmonic, the third harmonic, the fourth harmonic, and so on, in a descending order of magnitude.

The connection between ZCRs and Fourier's series is now explained on the basis of the following example, illustrated in Fig. 2. In blue, red and brown, respectively, a pure sine wave, a composition of two sine waves and a square wave that is essentially the sum of infinite sinusoids, are shown, all with the same length. Interestingly, the three curves have exactly the same number of ZCRs, however, according to Fourier's theory, their frequency contents are considerably different. Based on the example, the learnt lesson is: the first harmonics of a *non pure* signal are dominant over the others, whilst mandatory to define its general waveform shape. Consequently, it is often the minor oscillations produced by the higher harmonics that do not generate zero-crossings. Therefore, the ZCR of a given signal is much more likely to provide information on its fundamental frequency than a detailed description of its complete frequency content.

Another relevant concept is the direct relationship between the fundamental frequency of a signal and its ZCR. Since sinusoids are periodic in 2π, each period contains two zero-crossings, as shown in Fig. 3. Thus, if a 1D signal $s[\cdot]$ of length M crosses G times the amplitude zero, it contains $\frac{G}{2}$ sinusoidal periods at that frequency. Considering that, at the time the signal was converted from its analog to its digital version [14], the sampling rate was R samples per second, then $\frac{1}{R}$ is the period of time between consecutive samples, entailing that $M \cdot \frac{1}{R} = \frac{M}{R}$ is the time extension of the analog signal in seconds. Concluding, in $\frac{M}{R}$ seconds there are $\frac{G}{2}$ sinusoidal periods, implying that, proportionally, there are $\frac{G \cdot R}{2 \cdot M}$ periods per second, i.e., the frequency, F, caught by the ZCRs is

$$F(ZCR(f[\cdot])) = \frac{G \cdot R}{2 \cdot M} \quad Hz. \tag{2}$$

Obviously, the previous formulation is only valid if the sinusoids are not shifted on the amplitude axis, i.e., no constant value is added to them. Equivalently, the signal under analysis is required to have its arithmetic mean equal zero, implying that an initial adjustment may be necessary prior to counting the ZCRs, otherwise they would not be physically meaningful. The simplest process to normalise a signal $s[\cdot]$ in order to turn its mean to zero is to shift each one of its samples, subtracting its original mean, i.e.,

$$s_k \leftarrow s_k - \frac{\left(\sum_{j=0}^{M-1} s_j\right)}{M}, \qquad (0 \leqslant k \leqslant M-1) \quad . \tag{3}$$

In order to illustrate the concepts I have just exposed, the readers are requested to consider the signal $s[\cdot] = \{\frac{12}{10}, 3, \frac{12}{10}, 3, \frac{12}{10}, 3, \frac{12}{10}, 3, \frac{12}{10}\}$, of length $M = 9$, that was sampled at 36 samples per second and is illustrated in Fig. 4. Its arithmetic mean is $\frac{\frac{12}{10}+3+\frac{12}{10}+3+\frac{12}{10}+3+\frac{12}{10}+3+\frac{12}{10}}{9} = 2 \neq 0$, i.e., the normalisation defined in Eq. (3) must be applied before the ZCRs are counted. Thus, $s[\cdot]$ becomes $\{\frac{12}{10}-2, 3-2, \frac{12}{10}-2, 3-2, \frac{12}{10}-2, 3-2, \frac{12}{10}-2, 3-2, \frac{12}{10}-2\} = \{-\frac{8}{10}, 1, -\frac{8}{10}, 1, -\frac{8}{10}, 1, -\frac{8}{10}, 1, -\frac{8}{10}\}$, which has its mean equal zero and is also shown in Fig. 4. ZCRs are now ready to be counted, according to Eq. (1), resulting in $G = 8$ zero-