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Post-processing of time-frequency representations in instantaneous frequency estimation based on ant colony optimization

Miloš Brajović, Vesna Popović-Bugarin*, Igor Djurović, Slobodan Djukanović

University of Montenegro, Faculty of Electrical Engineering, 20 000, Podgorica, Montenegro

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ABSTRACT

Instantaneous frequency (IF) estimation of non-stationary signals embedded in high noise is addressed. When present, high noise represents a dominant error source in the IF estimation. Additive Gaussian noise with variance proportional to the signal power is assumed. An estimation approach based on the ant colony optimization (ACO) and time-frequency (TF) analysis is proposed. The ACO algorithm is adapted for the IF estimation starting from the Wigner distribution (WD) of the considered signal. The proposed technique is also applicable to numerous other representations, without any change in the parameter setup. This method surpasses the influence of high noise in the IF estimation; for that purpose, we have designed a pheromone deposition gradient and a mechanism for the variation of the agents' population size. The introduced approach improves the fast-varying IF estimation accuracy, overcoming known issues in the state-of-the-art algorithms dealing with high noise. The basic principles of the proposed method are illustrated and performance validated through numerical examples.

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1. Introduction

Time-frequency (TF) signal analysis has drawn a significant attention during the last few decades [1–43]. Various TF representations enable efficient analysis and extraction of information contained within time variations of the signal's spectral content [4,6]. One of the key topics in this area is the instantaneous frequency (IF) estimation of a signal [4–10]. Numerous TF representations and algorithms have been proposed in order to facilitate the IF estimation, but no TF representation exists, nor the estimation algorithm, that resolves this problem for all classes of signals and under all circumstances [4,5]. These facts make the IF estimation problem still scientifically attractive [6].

The IF estimation arises in numerous application fields including communications based on frequency modulation (FM), radar and sonar systems, speech analysis and recognition, analysis of video signals, seismology, biology, bio-medicine [6,16,25].

Many TF representations have the property of concentrating the signal energy at and around the IF [15,29–31]. This is the reason why the IF estimation formulation, in classical estimation approaches, reduces to determination of the TF representation maxima [4,5,6]. The Wigner distribution (WD) has been widely used as an IF estimator of FM signals, since the signal representation in the TF plane is highly concentrated [8,26,27]. However, due to higher-order signal phase derivatives, the WD contains inner interferences. Moreover, when multicomponent signals are considered, the undesired cross-terms appear in addition to signal components referred to as the auto-terms. The cross-terms can mask the auto-terms in the TF plane [3,25]. Besides the principles presented in [4] and [6], a comprehensive analysis of the WD as an IF estimator is given in [7] and [8], where the estimation error sources were classified into four categories: bias, errors due to variations within the signal's auto-terms, errors due to frequency discretization and errors due to high noise. Techniques that deal with the first three error sources are presented in [4,9,27,28]. The influence of high noise has attracted a significant attention, since it represents a dominant error source when it occurs [7–9]. Errors due to high noise appear since the high noise induces false maxima (maxima outside of the auto-terms) in the TF plane. Under the term "high noise" we assume additive Gaussian noise of the constant variance proportional to the power of the contaminated signal, as considered in [6–9,14].

An instance of the Viterbi algorithm (VA), originally introduced in [8], has been applied in the IF estimation in order to overcome the negative high noise impact. The performance of the VA-based approach in various estimation problems involving high noise has been confirmed during the recent years [6,9–13]. Another IF estimation approach based on a high-dimensional search of the IF curves in the TF plane has been proposed in [30], for the case

* Corresponding author.
E-mail address: pvesna@ac.me (V. Popović-Bugarin).

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of wavelets. The search of curves is based on a stochastic relaxation procedure. This approach has certain robustness to high noise. The generalization of this approach towards the TF representations with an introduction of a new stochastic search procedure has been presented in [31].

Artificial ant colonies (AACs), a biologically inspired paradigm, represent multi-agent tools for problem solving without a centralized control [44–59]. The whole set of optimization techniques based on the AAC concept, widely known as the ant colony optimization (ACO), has been developed and applied in different scientific areas, especially where the hard-solving local optimization problems arise [46–56]. The AACs are one of many concepts in the so-called swarm intelligence, where a population of artificial agents forms a collective intelligence over a specific environment [44]. Important application fields in digital image processing include edge detection, pattern recognition and feature extraction [48–56]. For the problem considered in this paper, an especially interesting ACO application is in edge detection in digital images [49,54,56]. By taking into account that edges represent image segments with high contrast and/or color variations, the median difference in agents' neighboring points has been used as the main criterion for edge detection [50,54,56].

In this paper, the ACO algorithms proposed in [49] and [50] are adapted for the TF-based IF estimation. A new gradient which takes into account the IF properties is introduced in order to achieve a robust estimation in high noise: the IF should pass through as many as possible points of the TFR with highest magnitudes, while the IF variation between two consecutive points should not be too fast [8].

The estimation is performed based on a generated pheromone map, representing a new TF representation with significantly reduced disturbances. The initial version of the algorithm is proposed in [59]. In this paper, we improve the performance of the algorithm [59] by introducing variable population size [49,50]. In addition, we evaluate the performance of the proposed method versus signal-to-noise ratio (SNR), provide comparison with the state-of-the-art VA-based algorithm and illustration of cross-terms suppression in the case of multicomponent signals, as well as the IF estimation illustration for real-life signals. The concept of variable population size provides an additional control mechanism for the mass behavior of an AAC. The basic idea is to retain the agents moving across the TF points corresponding to the auto-terms, while tending to eliminate as many those not corresponding to the auto-terms as possible. The agent's ability to survive during the iterations is measured by its energy, which is related to the proposed gradient. In this way, the influence of the gradient on the mass behavior of agents is emphasized. The distributed nature of the proposed algorithm and carefully designed gradient make the estimation more robust to fast IF variations. In this way, it overcomes, at a certain level, the sensitivity of the VA to fast IF variations, which is confirmed for signals with fast IF variations. Additionally, the proposed approach suppresses inner interferences, as well as cross-terms in multi-component signals.

Basic theory concerning the IF estimation problem is given in Section 2. The ACO algorithm within the framework of the TF-based IF estimation is presented in Section 3. Section 3 also introduces the pheromone deposition gradient and the variable population concept, both adapted for the IF estimation, the estimation algorithm and a discussion on the algorithm parameters. Section 4 presents numerical examples with the estimation results and a statistical verification of the proposed method by a comparison with the WD maxima and the VA estimators. Section 5 concludes the paper.

2. Background theory

Consider a complex amplitude and frequency modulated signal [6–9]:

$$s(t) = A(t)e^{j\phi(t)}, \tag{1}$$

where $A(t)$ is a slowly varying amplitude with respect to phase variations, i.e. $|dA(t)/dt| \ll |d\phi(t)/dt|$ and $\phi(t)$ is the signal instantaneous phase. Note that for real-valued signals positive frequencies are taken into account or the corresponding Hilbert transform of the signal is calculated. Some alternative signal models are also discussed in the literature [17–22]. The IF of $s(t)$ is defined as the first derivative of its phase, i.e.

$$\Omega(t) = d\phi(t)/dt. \tag{2}$$

The signal of interest is embedded in complex additive white Gaussian noise (AWGN) $\varepsilon(t)$ with zero-mean and variance σ^2, with independent and identically distributed (i.i.d.) real and imaginary parts, that is

$$x(t) = s(t) + \varepsilon(t). \tag{3}$$

The signal is sampled with the sampling interval Δt to obtain $x(n)=x(n\Delta t)$, where n represents discrete time variable. In the case when $s(t)$ contains multiple components, i.e. when $x(t)$ can be written as

$$x(t) = \sum_{l=1}^{S} s_l(t) + \varepsilon(t), \tag{4}$$

where S represents the number of components $s_l(t)$ defined by (1), the IF of each component can be calculated as the first derivative of the corresponding phase component. This concept has not full theoretical foundation, but it has clear justification when components are well-separated in the TF plane.

Further, we observe the WD of the signal $x(n)$, well known for its advantageous properties in the IF estimation of noisy signals. The IF approach that we present may be applied on other TF representations as well.

The WD of $x(n)$ [8] is defined as

$$WD(n,k) = \sum_{m=-K/2}^{K/2-1} w(m)x(n+m)x^*(n-m)e^{-j4\pi mk/K}, \tag{5}$$

where $-K/2 \le k \le K/2-1$ represents discrete frequency index, K denotes the length of a real-valued symmetric window $w(n)$, whereas * denotes complex conjugation. Without loss of generality even K is assumed. It is also assumed that the discrete signal length is N_s. For a given instant n, the IF ($\omega(n)$ or $\Omega(n\Delta t) = \omega(n)/\Delta t$) is estimated as the WD maximum position [6,8,25]:

$$\hat{k} = \arg\max_k WD(n,k). \tag{6}$$

This simple IF estimator is a common tool in practice. However, a high noise causes the WD maxima to be located away from the IF points, thus resulting in erroneous IF estimation [7,8].

The state-of-the-art approach overcoming the IF estimation problem in high noise is an instance of VA, originally introduced in [8], whose performance is reviewed in [6]. This algorithm combines a non-parametric method based on the WD maxima with the minimization of IF variations between consecutive points. As the VA incorporates a criterion that assumes slow IF variations between consecutive points, it is sensitive to fast IF variations.

3. IF estimation by using ant colony optimization algorithm

3.1. The review of basic ACO concepts, notation and terminology

Basic ACO algorithm is explained in [46], while details on ACO applications in edge detection and feature extraction can be found

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