Optik 167 (2018) 60–72

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Multiband imaging and linear unmixing of optical fiber intrusion signal

Yuan Zhang, Chengbin Sun, Dan Yang, Hongquan Qu *

School of Electronic and Information Engineering, North China University of Technology, Beijing, 100144, China

ARTICLE INFO

Article history:
Received 21 December 2017
Received in revised form 13 March 2018
Accepted 21 March 2018

Keywords:
Optical fiber pre-warning system (OFPS)
Feature extraction
spectrum unmixing
Nonnegative matrix factorization (NMF)

ABSTRACT

Feature extraction of the optical fiber intrusion signal is one of the most basic problems in the optical fiber pre-warning system (OFPS). This paper proposes a spectrum analysis method in the OFPS that adopts the time-frequency analysis technique to realize multiband imaging of the intrusion signal at first. Subsequently, the characteristic spectrum of the intrusion signal can be obtained as the intrusion feature from the imaging results. Since the practical intrusion spectrum is usually a mixture of multiple intrusion types, in order to extract the spectrum corresponding to each intrusion type, the mixed spectrum is characterized by a linear mixing mode. Then, we exploit the nonnegative matrix factorization (NMF) in the mixture analysis. Moreover, we add physical constraints to the NMF and solve it by gradient descent algorithm. Finally, we extract the characteristic spectrums from the mixed spectrum resulting to the spectrum unmixing. The real data experiments verify the effectiveness of this method.

1. Introduction

The optical fiber pre-warning system has been successfully applied on the oil and gas pipeline monitoring [1]. It utilizes the optical cable paralleled laying with the pipeline to collect the backscattered light induced by the external vibrations, which are considered to be the intrusion signals. And these vibrations are usually generated from different behaviors, such as animals or human footsteps, construction excavation and so on. The vibration intensity and period are basically related to the corresponding intrusion behaviors. Moreover, the distance between the occurrence of the intrusion and the system transmitter determines the time delay of the optical fiber signals. Thus, the OFPS has the ability to locate the intrusion position. The previous works focus on improving system detection performance [2–4]. Based on detection of the intrusion signals, a further recognition can be realized by introducing appropriate identification algorithms [5,6]. Although most of researches have achieved a high recognition rate in this field for a certain type of intrusion signals, they do not take into account the case of mixed intrusion signals.

The most probable types of intrusion signals include footsteps signals from human or animals, construction tools signals (such as drill shock or shovel digging) and passing vehicles signals. In a real environment, the intrusion will not behave as a certain single type, but a combination of multiple type of signals. For the signal collected by the OFPS is a one-dimensional signal in time domain, signal separation in single dimension is very complex. Most of the existing identification methods do not consider the separation problem of mixed signal. However, the separation of mixed signals has a very important practical

* Corresponding author.
E-mail address: qhqphd_ncut@163.com (H. Qu).

https://doi.org/10.1016/j.ijleo.2018.03.082

significance. On one hand, we can exploit the isolated signal separated from the mixed signals to accurately determine the specific intrusion type. On the other hand, with the existing optical fiber signal processing methods, we can further extract respective parameters from the separated signal component. In order to study this problem, this paper first uses a multiband imaging method to obtain the band-wise intensity distribution for the optical fiber intrusion signal, which is referred to as the spectrum. The main processes include: 1) To perform the time-frequency analysis on the optical fiber intrusion signal to generate a time-frequency map in each spatial location. 2) The time-frequency map is integrated along the frequency direction to obtain a two-dimensional temporal-spatial image of the intrusion signal in each frequency band. Then, all the bands are stacked up to form a temporal-spatial-band three-dimensional data cube. 3) Based on the data cube in 2), the intensity value in each band is extracted to form a spectrum as the feature of the intrusion signal. For the signal with sole intrusion type, the extracted spectrum is called as the characteristic spectrum. For the mixing case, after obtaining the mixed spectrum, we draw the idea of the endmember spectrum extraction in the hyperspectral field, and separate the mixed spectrum to get the pure spectrum of the intrusion signal, which is called the unmixed spectrum. Finally, we realize the spectrum unmixing.

Different intrusion signals have different spectral distributions, and there are also differences in the effect of various soil media on the intrusion signal. Thus, the characteristic spectrums of the intrusion signal received by the OFPS are ultimately determined by the specific form of the intrusion type and the physical location of the intrusion source. The characteristic spectrum actually shows the energy distribution of the intrusion signal in different frequency bands, which is an important feature to distinguish different type of signals. If there are multiple intrusion signals in the same resolution unit, the obtained spectrum is the superposition result of multiple types of the characteristic spectrums. The spectrum unmixing is precisely to achieve the separation of different characteristic spectrums from the mixed spectrum and has been studied in the hyperspectral field. Hyperspectral imaging can obtain the absorption coefficient of the substance with respect to multiple frequency bands in the same resolution unit. If the resolution unit contains only a single substance, the spectral line is the characteristic spectrum corresponding to the material. However, the resolution unit in actual imaging will usually mix a variety of substances, so the resulting spectrum is the superposition of a variety of characteristic spectrums [7]. In this sense, the characteristic spectrum analysis of optical fiber intrusion signal is the same as that of hyperspectral imaging. The spectrum unmixing process consists of two aspects, that is, obtaining all possible characteristic spectrums and the corresponding abundances. If the spectrum is a priori information, it can be relatively easy to obtain the abundance [8,9]. Such methods include maximum volume by Householder Transformation [10], Gaussian eliminate method [11], fast Gram determinant based algorithm [12], NFINDR [13,14], pixel purity index [15], orthogonal bases algorithm [16], iterative error analysis [17], simplex growing algorithm [18], successive projection algorithm [19]. However, the characteristic spectrum in practice is usually unknown. There are many ways to study the problems in this case, mainly concentrated in minimum volume transform [20], minimum volume simplex analysis [21], minimum volume enclosing simplex [22,23], simplex identification via split augmented Lagrangian [24], iterated constrained endmember [25], geometric optimization model [26].

In recent years, the nonnegative matrix factorization class caused great attention which is originally proposed to solve the feature extraction problem in the field of face recognition [27]. Since this method ensures the nonnegativity of the decomposition matrix, it avoids the fact that the matrix decomposition results are contrary to the physical reality. The implementation algorithm is divided into three categories, i.e., multiplicative update algorithm (MUA), alternating least squares algorithm (ALS) and gradient descent algorithm [28]. The main problem with multiplicative update algorithm is the possibility of locking zero elements on the convergence path, which means once an element in the decomposed matrix becomes zero, it must remain zero. Alternating least squares algorithm can avoid this problem, but the decomposed matrix may appear negative elements in the process of solving the least square equation. In this paper, we use the nonnegative matrix factorization based on gradient descent for spectrum unmixing. Considering the physical constraints on the abundances, that is, the sum-to-one constraint, we introduce this constraint condition into the optimal object function, and derive the corresponding solving algorithm using gradient descent. In the end, we realize the unmixed spectrums extraction from the mixed intrusion signals.

This paper is organized as following. In Section 2, we introduce the multiband imaging of the intrusion signal. The details of nonnegative matrix factorization based on gradient descent for spectrum unmixing are given in Section 3. The experimental analysis of actual data is described in Section 4. Finally, the conclusion is provided in Section 5.

2. Multiband imaging of the optical fiber intrusion signal for spectrum analysis

The diagram about the multiband imaging of the optical fiber intrusion signal is shown in Fig. 1. The OFPS uses the underground laid-in cable to perceive the external intrusion signal. The vibration around the fiber forces the refractive index of the fiber changing at the corresponding position, which further results in the intensity variation of the backscattered light. At the same time, this intensity variation modulated by the vibration will carry the information of the specific intrusion type. If the vibration form consists of a variety of movements, as shown in Fig. 1 including human footsteps, shovel digging and electric breaker, the system will receive a signal with mixed intrusion form. The initial optical fiber intrusion signal collected by the system is a range-time two-dimensional matrix data, where the range represents the spatial distance of the cable laying, and the time denotes the vibration occurring moment at a certain distance.

Considering the intrusion signals have many different frequency distributions, the time-frequency analysis is performed on the optical fiber intrusion signal to obtain the time-frequency distribution at each spatial position, on which energy band-