Detection and recognition of mechanical, digging and vehicle signals in the optical fiber pre-warning system

Qing Tian, Dan Yang, Yuan Zhang, Hongquan Qu *

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

**ABSTRACT**

This paper presents detection and recognition method to locate and identify harmful intrusions in the optical fiber pre-warning system (OFPS). Inspired by visual attention architecture (VAA), the process flow is divided into two parts, i.e., data-driven process and task-driven process. At first, data-driven process takes all the measurements collected by the system as input signals, which is handled by detection method to locate the harmful intrusion in both spatial domain and time domain. Then, these detected intrusion signals are taken over by task-driven process. Specifically, we get pitch period (PP) and duty cycle (DC) of the intrusion signals to identify the mechanical and manual digging (MD) intrusions respectively. For the passing vehicle (PV) intrusions, their strong low frequency component can be used as good feature. In generally, since the harmful intrusion signals only account for a small part of whole measurements, the data-driven process reduces the amount of input data for subsequent task-driven process considerably. Furthermore, the task-driven process determines the harmful intrusions orderly according to their severity, which makes a priority mechanism for the system as well as targeted processing for different harmful intrusion. At last, real experiments are performed to validate the effectiveness of this method.

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**1. Introduction**

Oil and gas pipeline leakage warning is one of the important applications of optical fiber pre-warning system (OFPS) [1]. As the most economical transportation mode of oil and natural gas, pipeline transportation has a positive impact on the development of national economy. However, pipeline leakage is a potential trouble which not only causes the energy waste, environment pollution and economic losses, but also may be security risks to nearby residents, hence, oil and gas pipeline leak warning is essential [2]. There are some traditional methods, such as monitoring with pressure, flow, temperature and so on [3]. However, these requires special placement for corresponding sensors which unfortunately could only detect intrusions within local finite range. The OFPS exploit the laying of the underground cable to detect and identify the external intrusion signals so that it can compute the place and time of the occurrence of any abnormal event [4]. The soil medium act as a carrier of vibration information to propagate the intrusion signals which act further on the underground cable. And the vibration modulates the optical signal transmitted in the fiber and ultimately causes the optical signal to carry the intrusion information [5,6]. Thus, the OFPS can realize full-path and super long-distance monitoring compared with the traditional method. More practically, the optical fiber cables are always deployed for normal communication upon the pipelines. Therefore, we can utilize some of them as our sensors without additional installation, which significantly reduces our system cost.

The research in OFPS mainly focuses on acquisition of measurements and intrusion information. The former mostly focuses on the design of fiber sensor, and is divided into two parts, i.e., interference and reflection. Documents [7–10] pay attention to Mach–Zehnder interference architecture. Although the real-time monitoring can be realized by this architecture, it is difficult to locate concurrent harmful intrusions, which is afterwards realized on detection of the reflection-based intrusions using phase-sensitive optical time-domain reflectometer (ΦOTDR) with higher resolution [11–14]. In this case, location accuracy can reach around 10 m and the amount of received data per millisecond is greater than 200 KB, which means that the system not only needs to deal with large amount of measurements, but also requires real-time processing ability. Based on these considerations, this paper focuses on the effective method for intrusion localization and recognition.

There exist two research directions for intrusion information acquisition which focus on detection performance improvement and...
recognition performance enhancement respectively. For the algorithm laying emphasis on detection performance, it realizes accurate location of the intrusion signals by obtaining alarm information with low false alarm rate [15,16]. However, there are many kinds of intrusion, such as mechanical, manual, vehicle, etc., and the damage degree of them is various. The mechanical signals produced by electric power, such as electric pick and electric drill, are of great destructive power posing a tremendous threat to the underground cable. Owing to the obviously low strength of handwork, the manual signal such as pick mattock and shovel signals is less destructive, and its damage degree is lower than the mechanical signal. Vehicle signal is a general kind of intrusion signal on the road. With the characteristic of the vehicle such as large contact area and short acting time, the threat to the underground cable posed by its vibration is the minimum with the lowest damage degree. On the one hand if the high-level measure is adopted to cope with all alarming, it may lead to immense waste of manpower and material. While, on the other hand the intrusion with high damage degree cannot be stopped timely if we use the general measures totally. Hence, it is necessary to take different measures in dealing with various intrusions by giving priority to the events with high damage degree. For the algorithm which focusing on identification performance, it realizes the recognition of the intrusion events by extracting effective characteristics of the signals and designing high-performance classifier for identification [17–20]. However, in the case of mass intrusion, the input including all the data or the detection result with high false alarm rate will lead to excessive calculation, long time-consuming and high misjudgment rate. And the system real-time requirement is difficult to satisfy by the above mentioned methods. Especially for the intrusion event with high damage degree, the system cannot make a timely judgment. Therefore, we need to design an algorithm to accurately and efficiently select harmful intrusions from sensory data and identify high-damage intrusion event according to the prior knowledge.

When human receive a large number of sensory information, our brain can quickly locate salient area and carry out cognitive analysis based on prior knowledge. This cognitive process is called visual attention architecture (VAA) in the field of signal processing, which plays an important role in object tracking and identification. The most representative architecture is the saliency model of Itti [21]. And the model is further improved in [22]. The VAA has been widely used in signal processing, such as target detection [23] and recognition [24], and can be divided into two parts, i.e., data-driven attention and task-driven attention [25–28]. The data-driven attention is driven by ‘sensory data’ which guides the salient area. In other words, a strong contrast area attracts data-driven attention. On the other hand, task-driven attention is determined by ‘cognitive factor’. To meet the requirements of data processing efficiency and recognition performance in OPFS, we introduce the VAA into OPFS for the first time and propose an intrusion signal detection and recognition method inspired by the mechanism of cooperative work between data driven and task driven in VAA. In data driven process, the harmful intrusions can be accurately and efficiently selected from all the sensory data by detection method to reduce the amount of input data for subsequent process. Firstly, the measurements in the spatial dimension is performed according to the background homogeneity, and the constant false alarm rate (CFAR) detection method can be selected by coefficient of variation (CV). In order to reduce the computational time, the cell average (CA)-CFAR is chosen to be a relatively low computational complexity in homogeneous background. The adaptive greatest-of/smallest-of(GO/SO)-CFAR with better detection performance under the clutter edge of heterogeneous background ensures the detection accuracy. Secondly, the harmful intrusion signal and harmless interference signal are both detected in time dimension. Herein, probability sequential rate test (SPRT) and Kolmogorov–Smirnov (K–S) test are selected based on occurrence frequency of interferences. In task-driven process, the identification algorithm guided by prior knowledge is adopted to realize recognition and classification of intrusions signal. It makes a priority mechanism for the system as well as targeted processing for different harmful intrusion. Firstly, the intrusion signal feature is extracted based on prior task. According to the severity, multi-feature extraction order is determined. Secondly, specific features are extracted to identify corresponding intrusion signals, for example the pitch period (PP) of mechanical, duty cycle (DC) of MD and zero-crossing rate (ZCR) of PV. Finally, we collected measurements of multiple intrusions in Shang Wei Dian Village, Mentougou District of Beijing, to verify reliability of the proposed method. The experimental results show that the situation and time of intrusions can be accurately located and data quantity of later process can be reduced in data-driven process. Moreover, task-driven process can effectively identify different types of intrusion. With the integration of these two processes, the proposed method can not only realize real-time and efficient manipulation of data, but also significantly improve the recognition accuracy compared with representative methods.

The remainder of the paper is organized as following. In Section 2, the whole process of detection and recognition method is described. The principle of data-driven and task-driven process is given in Section 3, respectively. In Section 4, the experiments with actual data are performed. Finally, conclusions are provided in Section 5.

2. The processing flow of OPFS

In this paper, ΦOTDR technique is applied to monitor multi-concurrent harmful intrusions in OPFS. Exterior intrusion can cause ground vibration, which further leads to deformation of underground optical fibers resulting in the changes of the refractive index. Consequently, the Rayleigh backscattered intensity will change accordingly, which is defined as following.

\[ p_i (t) = p_{i1} (t) + p_{i2} (t) \]

\[ = \sum_{n=1}^{N} a^2 \cdot \exp \left[ -2ac \cdot \tau_{ij} / W \right] \cdot \text{rect} \left[ t - (k - 1)T - \tau_{ij} / W \right] \]

\[ + 2 \sum_{n=1}^{N} \sum_{i=1}^{N} \sum_{j=1}^{N} a^2 \cdot \cos \phi_{ij} \cdot \exp \left[ - \frac{a \cdot c \cdot (\tau_{ij} + \tau_{ij})}{n_f (t)} \right] \cdot \text{rect} \left[ t - (k - 1)T - \tau_{ij} / W \right] / W \]

\[ (1) \]

where, \( p_{i1} (t) \) is independent superposition term, \( p_{i2} (t) \) is coherent superposition term, \( f \) is the frequency of monochromatic pulse light, \( T \) is pulse period, \( W \) is pulse wide, \( k \) is pulse sequence, \( a \) is 1st scattering pulse light range which is produced by incident light in scattering center without losses, \( \tau_i \) is time delay of \( i \)th scattering pulse light within single pulse period, \( N \) is the number of scattering center in the whole fiber, \( a \) is the attenuation constant of fiber, \( c \) is light speed in vacuum, \( n_f \) is refractive index of fiber, \( \phi_{ij} \) is phase difference between \( i \)th backscattered light and \( j \)th backscattered light. The relationship between \( \phi_{ij} \) and \( n_f \) is shown as Eq. (2).

\[ \phi_{ij} = 2\pi \times f \cdot n_f \cdot (z_i - z_j) / c \]

(2)

where, \( z \) is spatial position and \( (z_i - z_j) \) is spatial resolution.

According to Eq. (1), backscattered light intensity consists of two parts, i.e., independent superposition and coherent superposition term. Due to light source with narrow linewidth in ΦOTDR, coherent superposition effect is distinct in different scattering points. According to Eq. (2), phase difference changes following variation of refractive index in coherent superposition term. Furthermore, the light intensity of the Rayleigh backscattered is influenced by Eq. (1). The backscattered light intensity changes can be obtained by difference of light intensity with same situation but different time. It reveals exterior intrusion information.

Overall structure flow chart of OPFS is shown in Fig. 1. Oil and gas pipeline is usually buried in same ditch with fiber cable. The
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