Research Article

Research and Software Design of an Φ -OTDR-Based Optical Fiber Vibration Recognition Algorithm

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Distributed optical fiber vibration signal plays a significant role in the communication and safety of any perimeter security monitoring system. It uses light as an information carrier and optical fiber as a means of signal transmission and communication. Phase-sensitive optical time-domain reflectometry (Φ -OTDR) is used to detect the signals generated during events (intrusions or nonintrusion). This paper proposes the time-frequency characteristic (TFC) method for the recognition of the fiber vibration signal and designs and implements the corresponding software function module. The combination of time-domain features and time-frequency-domain features is called TFC; and it is based on the Hilbert transform and on the empirical mode decomposition (EMD) of time-frequency entropy and center-of-gravity frequency that is described. A feature vector is formed, and multiple types of probabilistic neural networks (PNNs) are performed on it to determine whether intrusion events occur. The experimental simulation results show that the monitoring system software can intelligently display the data collected in real time, which demonstrates that the proposed method is effective and reliable in identifying and classifying accurately the types of events. The data processing time is less than 2 s, and the accuracy of the system identification can reach 99%, which ensures the system's validity.

1. Introduction

In order to respond to the “13th five-year” development plan of the security industry and meet the growing demand of the people for security, it is of great significance to maintain the security of the equipment area intelligently and reliably and to maintain social security to ensure the safety of life and properties. Zhang [1] and Yin [2] have approved the use of the traditional methods that are personnel patrol, surveillance video, capacitive voltage sensor networks, etc. Its low reliability, high maintenance costs, and limited monitoring distance are the inevitable drawbacks of these methods. Such measures are subject to time, manpower, and other factors; it is difficult in that case to avoid loopholes. For some environmentally sensitive areas, such as power plants, oil depots, weapons and ammunition depots, bank vaults, airports, and oil platform, it is even more necessary to strengthen security monitoring to prevent illegal intrusions. These areas are

extremely sensitive and have a wide range of equipment. Traditional perimeter security systems are difficult to adapt to harsh environments and have a small monitoring range. Therefore, this paper adopts a distributed optical fiber sensing technology that offers a wide range of monitoring, strong anti-interference capability, high sensitivity, and stable performance [3–5].

The common distributed fiber perimeter security monitoring system mainly consists of four parts: signal detection, signal transmission, signal processing, and signal alarm. Signal detection is the detection and sensing of different vibration signals in the device area through fiber optic sensing. Signal transmission is to transmit a vibration signal from the signal detection module to the signal processing module. The signal processing is primarily composed of computer software, whose fiber vibration signal processing algorithm is at the heart of the study; the detected vibration signal is processed, analyzed, and evaluated. The

signal alarm is an alarm module generated by the system to determine an intrusion event [6]. Various techniques and algorithms for signal detection have been presented by many researchers and can be implemented when designing the distributed optical fiber sensors which include coherent optical time-domain reflectometry (C-OTDR) [7], Mach-Zehnder (MZ) interferometers [8], fiber Bragg grating arrays, Michelson interferometers, and Sagnac loops [9]. But, the application of these techniques for recognition of the nuisance signals used as a security system in large infrastructures is complex and contains many practical problems in some noisy or hostile environments that must be resolved. Recently, Mahmoud et al. [10] has made several attempts using the high-performance distributed optical fiber sensors in outdoor and underground infrastructures to solve the problems of recognition of a triggered alarm. Mahmoud and Katsifolis [11], and also Wu et al. [12], have used features such as short-term energy and short-term zero-crossing rate in the time-domain analysis in order to improve the system performance. But, the time-domain features of the vibration signals of different intrusion types show the same trend of change before and after any intrusion, and it is difficult in that way to accurately identify a variety of intrusion types. A two-level identification scheme is proposed, which in first passes through the time-domain features, after which the suspected perturbation position is extracted. Then the short-term Fourier transform is used by Liang et al. [13] to qualitatively analyze the spectral features. But DiCarlo and Weber [14] have extracted in the complex wavelet domain the energy distribution and vibration duration of different frequency bands as signal characteristics; and finally the support vector machine (SVM) is used to classify them. The aforementioned intrusion detection systems provide high-accuracy system identification, but they lack real-time operation and suffer from Fourier transform limitations caused by the uncertainty principle. In fact, the Fourier transform is a global transformation, which cannot effectively extract the instantaneous frequency and instantaneous state of nonlinear and nonstationary optical fiber vibration signals.

Considering the drawbacks mentioned above, a research and analysis of vibration signals must necessarily be carried out, by using other more efficient methods. Therefore, it is necessary to study efficient algorithms for signal processing; hence, the research and software design of an Φ -OTDR-based optical fiber vibration recognition algorithm is proposed. To achieve the recognition events at the real time, an effective two-level vibration recognition method and technique are proposed and described in this paper, as well as the corresponding software design. The sensing system is collected under various weather conditions. The optical mode vibration signal is subjected to empirical mode decomposition (EMD) and Hilbert transform [15, 16] to obtain the time-frequency distribution and the time-frequency spectrum. The time-frequency entropy is used to quantify the uniformity of signal energy distribution in the time-frequency plane; while the center-of-gravity frequency characterizes the concentrated position of the fiber vibration signal energy in the frequency band. After the analysis and

extraction of the time-domain characteristics and time-frequency-domain characteristics of the optical fiber vibration signal, the specific design of a two-level vibration pattern recognition scheme based on time-frequency characteristics is performed.

2. Monitoring System Design and Methodology

2.1. Hardware Framework of the Monitoring System. The distributed fiber perimeter security system consists of signal data acquisition hardware system and computer software of the monitoring system. Its overall block diagram is shown in Figure 1. The Φ -OTDR technology is used to collect the fiber vibration signal.

The Φ -OTDR is chosen because of its accuracy, measurement range, ability to resolve, and measure closely spaced events; besides, it can simultaneously detect intrusion events at multiple points [17]. The features such as high quality, accuracy, and high-coherence laser source are achieved by using an electro-optical modulator (EOM) as an intensity modulator. Φ -OTDR uses the coherent effect of Rayleigh scattering to detect vibrations; its system is designed independently for high-speed data transmission. The block diagram of the acquisition system hardware is displayed in Figure 2 (EOM: electro-optic modulator; PD: photodetector)

2.2. Φ -OTDR-Based Perimeter Security System Technical Parameters and Routes. Based on the analysis of sensor distance, spatial resolution, recognition accuracy, and response time, the technical parameters of the Φ -OTDR are presented in Table 1 [18].

3. Design of Two-Level Vibration Pattern Recognition Scheme Based on Time-Frequency-Domain Features

3.1. Fiber Vibration Mode Recognition. The pattern recognition method of perimeter security monitoring system is mainly divided into the following parts: signal acquisition, signal preprocessing, signal feature extraction, multiclass model training, and classification decision. The training of the classification model is based on the feature set of a portion of the data samples, and a standard model is trained as a template. The classification decision is to execute the same preprocessing and feature extraction on an unknown signal when it needs to be identified and to perform pattern matching with the standard classification model to output the matching result and realize the intrusion type judgment [19]. The proposed probabilistic neural network (PNN) is performed as in the study of Tabi Fouda et al. [20]; it is suitable for real-time processing and is used for pattern recognition.

3.2. Two-Level Pattern Recognition Scheme. After the preprocessing of the fiber vibration signal, the first-level prejudgment is performed through the time-domain feature, and the vibration signal of the suspected

FIGURE 1: Overall structure connection diagram of fiber perimeter security system based on Φ -OTDR. FIGURE 2: Block diagram of the fiber vibration detection system based on Φ -OTDR.TABLE 1: Technical specifications of the distributed fiber perimeter security system based on Φ -OTDR.

Index parameters	GA/T 1217-2015	System indicators
Detection distance/positioning accuracy	>5 km and ≤ 20 km/ ≤ 25 m	10 km/8 m
Intrusion response time	≤ 3 s	≤ 2 s
Scanning frequency	—	10 kHz
Recognition accuracy	—	>95%

intrusion event is predicted to perform the second-level vibration pattern recognition scheme. By extracting the time-frequency-domain features and combining the time-domain features to form the feature vectors, they are input into the multiclass model trained in the sample database to realize the judgment of whether there is any intrusion and the type of intrusion. The method consists of four steps, and the overall process block diagram is presented in Figure 3.

FIGURE 3: Functional diagram of the fiber vibration mode recognition.

4. Acquisition and Preprocessing of Fiber Vibration Signals

4.1. Fiber Optic Vibration Signal Acquisition. In this paper, a fenced cable is built outdoors for collecting real and effective fiber vibration data. The nonintrusion (strong wind, heavy rain, and sunny weather) and intrusion (tapping and climbing) are the data collected to perform experiments. The system installation and the quality of the equipment are more important to avoid nuisance alarms and false alarms. Figures 4(a)–4(c) show three different examples of possible installation configurations of the sensor cable on a chain link fence. The configuration in Figure 4(b) was used in this paper because it improves the detection rate of fence climbing and tapping [21].

FIGURE 4: Example of different cable configurations on a chain link fence.

In this paper, the Φ -OTDR is collecting different fiber vibration data obtained at a sampling frequency of 10 kHz for a given period of time, and data of 90 position points are collected at a time. In order to facilitate the analysis, the fiber optic vibration signal at the same position is framed, and each frame contains 4096 items of data.

4.2. Preprocessing of Fiber Vibration Signals. The original vibration signal collected from the fiber generates a lot of noise (nuisance alarms and false alarms) that needs to be attenuated. After a large amount of data analysis, the sixth-order Butterworth high-pass filter with a cutoff frequency of 500 Hz is selected to filter the original vibration signal due to its better performance in noise reduction, as can be seen from Figure 5.

The perimeter security system data are easy to process when the noise of the original signal is reduced. Short-term energy and short-term threshold rate are used to characterize the intrusion intensity and fluctuations and perform the first-level prejudgment. It is discovered that when the system is in the normal state, the amplitude and the fluctuating frequency of the vibration signal are very small; when there are intrusions, the amplitude and frequency of the vibration signal will increase significantly. The first-level prejudgment of the time-domain features of the fiber vibration signal suspected of an intrusion is used for the second-level vibration pattern recognition as in the study of Tabi Fouda et al. [20].

5. Time-Domain Characteristics Analysis of Optical Fiber Vibration Signals

Taking into account the actual situation, this paper selects the short-term energy and the short-term threshold rate that characterize the strength and jitter frequency of the fiber, respectively. If the short-term energy E_n of one frame of the fiber vibration signal is greater than the threshold $E^* = 2 \times 10^8$ or the short-term threshold rate Z_n is greater than the threshold $Z^* = 100$, it is predicted to be a suspected intrusion signal; otherwise, no intrusion occurs. As presented in Table 2, both the short-term energy and the short-term threshold rate of the tapping and climbing signals exceed the stable value, and then it is difficult to identify the type of vibration.

5.1. Short-Term Energy. The short-term energy is the sum of the squares of the data amplitude over a period of time. The signal for normal conditions, tapping, and climbing are made during the same period of time and at a certain vibration position. The curves of short-term energy signals are shown in Figure 6.

5.2. Short-Term Threshold Rate. The short-term threshold rate is a number that includes the condition where the data in a given period meet the conditions under which the previous data are lower than the set threshold and the actual data are greater than the set threshold. The short-term

threshold rate of different fiber vibration signals is shown in Figure 7.

The short-term energy and short-term threshold rate of nonintrusion signals do not change significantly with time, and the two feature values are low, while the short-term energy and the short-term threshold rate of the tapping and climbing signals have obvious mutations with time. The two eigenvalues that are presented in Table 2 are larger at the mutation, but the mutations of the climbing and tapping signals are similar. In the short-term energy and short-term threshold rate curves, the nonintrusion signals are similar, the tapping signals are similar, and the climbing signals are also similar. This makes the study difficult to determine the type of vibration.

6. Time-Frequency Characteristics Analysis of Optical Fiber Vibration Signals

Since the time-domain characteristics of different fiber vibration signals exceed the set value, it is difficult to judge the type of intrusion. Therefore, the time-frequency characteristics are used to identify the intrusion type. Using the EMD and the Hilbert transform, the instantaneous frequency and instantaneous amplitude of the signal are obtained, as well as the time-frequency distribution of the fiber vibration signal is obtained. This makes it possible to obtain the temporal spectrum of the vibration signal of the fiber. This paper uses time-frequency entropy to quantify the uniform distribution of signal energy in the time-frequency plane, and the center of gravity frequency quantifies the concentrated position of the signal energy in the frequency band. The time-correlated gravity center frequency is selected to quantify the trend of the concentrated position of the signal energy over the frequency band with time. Finally, the time-domain features are combined with the time-frequency-domain features to form the total feature vector for pattern recognition and intrusion type determination; the general process block diagram is presented in Figure 8.

6.1. EMD and Hilbert Transform. To use the analytical signal method to obtain a significant instantaneous frequency, this requires the signal to meet the following conditions: ① the signal must be a single component signal; ② the signal must be zero mean and symmetric with respect to zero mean. In order to get a significant instantaneous frequency, the signal must be processed by EMD. EMD decomposes a signal from high to low frequency into a series of stationary, linear single component signals, namely, the intrinsic modal function (IMF); and the signal decomposition corresponds to the following equation of the EMD process:

$$S(t) = \sum_{i=1}^m \text{imf}_i(t) + r(t). \quad (1)$$

Hilbert transform:

$$H[\text{imf}_i(t)] = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{\text{imf}_i(\tau)}{t - \tau} d\tau. \quad (2)$$

Instantaneous amplitude:

FIGURE 5: Comparison of the results of three denoising methods. (a) Original signal. (b) Differential filtered signal. (c) Butterworth high filtered signal. (d) Wavelet threshold denoising reconstruction signal.

TABLE 2: Time-domain characteristics of a frame fiber vibration signal.

Features	Nonintrusion	Tapping	Climbing
Short-term energy	1.7×10^7	9.8×10^8	1.9×10^9
Short-term threshold rate	5	341	751

$$a_i(t) = \sqrt{imf_i^2(t) + H^2[imf_i(t)]}. \quad (3)$$

Phase function:

$$\Phi_i(t) = \arctan \frac{H[imf_i(t)]}{imf_i(t)}. \quad (4)$$

Instantaneous frequency:

$$\Omega_i(t) = \frac{1}{2\pi} \frac{d\Phi_i(t)}{dt}. \quad (5)$$

The flowchart of the EMD to obtain the IMF component is presented in Figure 9 [22].

After getting m IMF components, the Hilbert transform is used to construct an analytical signal for each IMF component. An analytical signal is a complex signal, and the

resulting amplitude function is the instantaneous amplitude; the derivative of the resulting phase function is the instantaneous frequency that can be seen from equations (2)–(5). The instantaneous amplitude and the instantaneous frequency change with time.

As demonstrated and explained in the study of Tabi Fouda et al. [20], there are nonintrusion, tapping, and climbing signals during the same period of time at a certain vibration position point initially selected. The analysis of their EMD and Hilbert time spectrum is presented in Window 3 and Window 4 of Figure 10.

But Window 3 shows the Hilbert time spectrum of the tapping vibration signal, and Window 4 displays the instantaneous frequency-time distribution of the tapping vibration signal. On the basis of Nyquist theorem, the effective frequency band of the time spectrum is 0–5000 Hz.

6.2. Time-Frequency Entropy and Center of Gravity Frequency. Entropy of information refers to the average degree of uncertainty in the system, while center-of-gravity frequency characterizes the concentrated position of the fiber vibration

FIGURE 6: Short-term energy distribution of different fiber vibration signals. (a) Nonintrusion. (b) Tapping. (c) Climbing.

FIGURE 7: Short-term threshold rate distribution of different fiber vibration signals. (a) Nonintrusion. (b) Tapping. (c) Climbing.

FIGURE 8: Overall block diagram of frequency-domain feature extraction for fiber vibration signals.

signal energy in the frequency band. This part was experimentally demonstrated in the study of Tabi Foua et al. [20].

7. Experimental Demonstration and Analysis of the Results

The experimental environment is a Windows 7 server, 64-bit operating system, and the processor is Intel(R) Xeon(R)

CPU E5-2620 v3 @ 2.40 GHz 2.40 GHz (2 processors) with 16 GB of memory; and the programming is carried out in Matlab R2014a(8.3.0.532).

7.1. Verification of the Program Validity. As presented by Tabi Foua et al. [23], in order to verify that the second-order vibration pattern recognition method based on time-frequency-domain features can effectively identify the intrusion type, 240 nonintrusion, 90 taps, and 90 climbing data samples are selected in this paper. Wherein, the non-intrusion signal of the same duration at a certain position is used as the nonintrusion data sample, the tapping signal of the same duration on the tapping point is used as the tapping data sample, and the climbing signal of the same duration at the climbing position is used as the climbing data sample. Each data sample is 24 frames long and has a frame length of 0.4096 s.

Framing the fiber vibration signal, there are 4096 data in one frame, each datum is recorded as x_n , $n = 1, 2, \dots, N$,

FIGURE 9: Flowchart for obtaining EMF components by EMD.

FIGURE 10: Offline monitoring part interface diagram.

$N = 4096$. Calculate the short-term energy E of each frame of data:

$$E = \sum_{n=1}^N x_n^2 \quad (6)$$

Calculate the short-term threshold rate Z of each frame of data:

$$Z = \frac{1}{2} \sum_{n=1}^N \left\{ |\text{sgn}(x_n - \delta) - \text{sgn}(x_{n-1} - \delta)| + |\text{sgn}(x_n + \delta) - \text{sgn}(x_{n-1} + \delta)| \right\}, \quad (7)$$

where $\text{sgn}(t) = \begin{cases} 1, & t \geq 0 \\ -1, & t < 0 \end{cases}$, and according to a large number of experimental analyses, the threshold of the short-term threshold rate is $\delta = 200$. If the short-time energy E_n of a certain frame fiber vibration signal is greater than the threshold $E^* = 2 \times 10^8$ or a short-time threshold rate Z_n is greater than the threshold $Z^* = 100$, it is predicted to be a suspected intrusion signal; otherwise no intrusion occurs.

7.2. Results Analysis. According to the pattern recognition method of the data sample, 120 nonintrusion data samples, 45 tapping data samples, and 45 climbing data samples are randomly selected as the training set, the PNN multiclass model is formed, and the remaining data samples are used as test sets. The test set is tested in the trained PNN multiclass model, and the time-frequency accuracy of different data samples obtained under time-frequency-domain characteristics is compared with the requirement of intrusion recognition accuracy in the technical indicators, as shown in Table 3. It can be seen from the table that the scheme can intelligently and effectively identify the type of intrusion, and the recognition accuracy rate of different intrusion types meets the requirements of technical indicators.

At the experimental stage, it was discovered that when the detection range of the system is 10 km with the disturbance range of 1 km, the system data processing time is about 0.9564 s, which is greater than the real-time data acquisition time of 0.4096 s. At that time, the probe response time is about 1.366 s (ignoring the delay redundancy) which is less than 2 s; therefore, the scheme in this paper realizes a good real-time performance.

8. Design of the Monitoring System Software Based on Time-Frequency Characteristics

The monitoring system software mainly consists of the following modules depending on the functions. Each module is implemented with a separate thread so that the operation of each function of the software is implemented independently and does not affect each other. The software block diagram is shown in Figure 11.

TABLE 3: Comparison of the intrusion recognition accuracy rate of experimental results with technical indicators.

Features	Events (%)		
	Nonintrusion	Tapping	Climbing
Technical indicators	≥ 95	≥ 95	≥ 95
Experimental results	100	97.01	95.99

FIGURE 11: Software block diagram of the distributed fiber perimeter security monitoring system.

8.1. *Function Modules Related to Intrusion Signal Detection Algorithm.* The main functions of each module are as follows.

8.1.1. *Data Acquisition Module.* It is used to transmit the signal detected by the Φ -OTDR from the network port to the monitoring system software and uses WinPcap to capture the original data, which can vibrate the fiber. The data are acquired online and processed in real time. This module can also be used to collect a large number of vibration signals of different intrusion events. The collected large number of optical fiber vibration signals is stored in the MySQL database as a data sample library, which facilitates offline signal analysis and provides raw data for studying fiber-optic vibration algorithms that are highly efficient and stable for the monitoring area.

8.1.2. *Data Processing Module.* The data processing module is used for algorithm processing of the optical fiber vibration signal. The module mainly implements the offline monitoring

part and the online monitoring part of the software. The block diagram of the data processing module is shown in Figure 12.

① The offline monitoring part is used to train multiple types of models, preprocess, extract time-domain and time-frequency-domain feature in the data sample library to form feature vectors, and store them in the MySQL database as feature sets. The characteristics of different intrusion types are learnt, multiple types of models are trained, and the model is optimized by continuously adding fiber vibration signals in the data sample library, thereby improving the recognition accuracy of different intrusion types of the system. ② The online monitoring part is used for real-time monitoring of the vibration around the fiber on the fence, and the data acquisition module is used to acquire the vibration data of the fiber in real time. The data processing module performs preprocessing and time-domain feature extraction on the real-time collected fiber vibration data, thereby performing the first-level prejudgment based on the alarm threshold parameter of the system parameter setting module. The first-level prejudged suspected intrusion signal performs secondary pattern recognition,

FIGURE 12: Block diagram of the data processing module.

extracts the time-frequency-domain features of the suspected intrusion signal, and forms a feature vector with the time-domain feature. It is matched with multiclass models to analyze the results of the alarm decision and to determine whether there is intrusion and identify the type of intrusion.

8.1.3. Alarm Processing Module. It mainly alarms the output of the data processing module. When the data processing module determines that an intrusion occurs, the alarm processing module is triggered to perform an alarm, and alarm information such as the intrusion type, the intrusion time, and the intrusion position is displayed in the alarm display column.

8.2. Other Function Modules. The main functions of each module are as follows.

8.2.1. System Parameter Setting Module. It is used to set and modify various parameters; and the set or modified parameters are stored in the MYSQL database.

8.2.2. Map Display Module. It is used to display the monitored device area, and when the system generates an alarm, it can intelligently display the specific location of the alarm.

8.2.3. Data Query Module. It is used by the user to query historical data and abnormal data stored in the MYSQL database.

8.2.4. Report Output Module. It is used to automatically generate a system operation report for the current month at the end of the month, which can be stored and printed.

8.2.5. User Module. The user module mainly protects the security of the software operation by password login and password modification and prevents unauthorized copying, destruction, and modification.

8.2.6. MYSQL Database. It is used to store data samples, feature sets, intrusion types, intrusion times, intrusion locations, anomaly data, historical data, and monthly reports. The establishment of data sample libraries and feature sets facilitates training of multiple types of models; intrusion types, intrusion events, and intrusion locations are primarily used to display alarm information when an alarm is raised. The abnormal database and the historical database are mainly convenient for users to view and analyze the intrusion situation; the monthly report library is mainly used for outputting the monthly report library for the user to view at any time.

9. Monitoring System Software Main Function Realization

The main functions of the monitoring system software include receiving the fiber vibration data collected by the hardware system, realizing the real-time discrimination and intrusion alarm of the fiber vibration data, monitoring

graphic display, sample library management, electronic map and alarm data management, and historical data query. The distributed fiber perimeter security monitoring system software is divided into two parts, namely, online monitoring and offline monitoring.

9.1. Offline Monitoring Function. The offline monitoring is used in order to optimize the pattern recognition model, thereby increasing the system identification accuracy. The main function of the offline monitoring part is to extract the time-domain features and time-frequency-domain features of different fiber vibration signals and perform pattern recognition on the feature vectors to train multiple types of models. By continuously adding new data samples to optimize multiple types of models, the recognition accuracy of the system is improved. Its interface diagram is displayed in Figure 10.

9.1.1. Window 1 Is a Data Acquisition Module Graphic. Click on “start acquisition,” and then the data acquisition module will start network capture and data collection. Click on “stop acquisition,” and then the data acquisition module will stop capturing packets and stop collecting data so that fiber vibration data can be collected. Afterward click “storage data” to save the data to the configured storage path so that it can be loaded at any time and processed offline. The data collected by the distributed optical fiber vibration detector and the data acquisition module of the Φ -OTDR are a different fiber vibration signal at a certain point of time. The data acquisition module can configure the starting position point, and the acquisition time can be controlled according to the start and the stop acquisition.

9.1.2. Windows 2, 3, and 4 Are Data Processing Module Graphics. Click on the “load data” button in Window 1 to select the data sample. Window 1 shows the energy distribution map for each time point at each location, then click on an intrusion location point on Window 1, and Window 2 displays the amplitude distribution of the intrusion location point all the time. 24 frames of data are continuously selected on Window 2, and the data processing module graphics are subjected to EMD and Hilbert transformation to obtain a Hilbert time spectrum as shown in Window 3; and the “instantaneous frequency-time” profile is obtained as well as shown in Window 4. Window 3 and Window 4 discriminate whether it is marked as an alarm sample or a non-alarm sample. If it is marked as an alarm sample, click “mark as alarm sample,” otherwise, click “mark as nonalarm sample.” The time-frequency entropy and center-of-gravity frequency of the continuous 24 frames of data at the intrusion location point are calculated internally and stored in the feature set of the MySQL database. By continuously loading data, the alarm sample and nonalarm sample are expanded and developed, the amount of data in the data sample is increased, as well as the pattern recognition, thereby continuously optimizing the multiclass model of training.

9.2. Online Monitoring Function. Its main function is to monitor the vibration of the light in real time; if an intrusion occurs, the intrusion status, time, and position are alarmed. Its function implementation is described below:

- (i) The data acquisition module obtains fiber vibration data online. Each time the vibration state of all the points in the monitoring area is collected, the data processing module displays the distribution of the differential short-time energy and the average vibration amplitude of the original vibration signal in the unit time window at different positions at the same time, as shown in Figure 13. By analyzing the amplitudes of the two waveforms, it is predicted whether there is any intrusion by comparing the set warning parameters.
- (ii) If it is predicted to be an intrusion, it is subjected to a secondary pattern recognition scheme to extract its time-frequency-domain characteristics. Then, pattern recognition is performed to match the trained multiclass models to determine whether there is intrusion and discriminate the intrusion type.
- (iii) If it is finally judged to be in an intrusion state, the alarm system is triggered. If the alarm system is triggered, an exception prompt window will pop up immediately, as shown in the exception prompt box in Figure 14. The alarm processing interface is shown in Figure 14. The real-time alarm window displays the alarm time, the start and end positions of the alarm, and the cause and processing status of the alarm.

The electronic map interface shows the fence map built where the experiments were carried out; real-time alarm information is displayed as well. Taking into account the visual effect of the user and system resources, the waveform is refreshed every 0.4096 seconds. When an alarm occurs, the intrusion location of the disturbance alarm is automatically identified on the map. In fact, the map display window reminds the security staff to handle the alarm in time.

9.3. System Parameter Setting Module. This parameter is used to set and modify various parameters, and the set parameters or modified parameters are stored in the MySQL database. System parameters include alarm threshold parameters, data retention parameters, and timing parameters. The alarm threshold parameter is used to set various parameters involved in the algorithm, such as short-term energy threshold and short-term threshold rate. The setting of this parameter is achieved according to the experimental environment built in this paper. The data backup parameter is an identification tag for storing various data in the MySQL database. These varieties of data include data samples, feature sets, intrusion types, parameter tables, anomaly data, historical data, monthly reports, and password tables. In order to facilitate the classification and collection of different data, the parameters involved in adding labels and different storage paths to various data are data backup parameters. The system replay

FIGURE 13: Distribution of differential short-time energy and average vibration amplitude of original vibration signals.

FIGURE 14: Alarm processing interface diagram.

time corresponds to the time parameter of the experimental area (Shanghai Maritime University), and the name and order of the data are stored in chronological order. If there is an error in the system time, it must be corrected. Figure 15 shows the interface of the system parameter setting module.

After modifying the form data, you need to save by pressing the “Save” button. Intrusion time threshold (seconds): set the value to 1 or 2 to enable the flag, 1 for “arming” and 0 for “disarming.”

9.4. Data Query Module. The data query module is used by the user to query historical data and abnormal data stored in the MYSQL database. The user can arbitrarily call historical data at any time point and automatically generate historical trends at different points in the same position, which can be compared and analyzed. Users can also call abnormal data, compare and analyze their intrusion type, their intrusion location, and their intrusion time, strengthen their protective measures against frequent intrusion events, view their locations where there are often intrusions, and strengthen their care. Figure 16 displays the interface of the data query module.

9.5. Report Output Module. This module is used to automatically generate a system operation report for the current month at the end of the month, which can be stored and

FIGURE 15: System parameter setting module interface diagram.

FIGURE 16: Data query module interface diagram.

FIGURE 17: Report output module interface diagram.

printed. Users can select the month to generate a report for that month, view and analyze it, and select the appropriate save path to store and print it. Figure 17 presents the interface of the report output module.

9.6. User Module. It mainly protects the security of the software operation by password login and password modification and prevents unauthorized copying, destruction, and modification. The user module provides three levels of right management functions; different levels of administrators can enjoy different levels of rights. The administrators from high level to low level are super administrators, that is, the first-level administrator, second-level

FIGURE 18: User module interface diagram.

administrators, and third-level administrators. Super administrators can manage secondary and tertiary administrators, add/or delete users, log in to the system with a password, or manage users by modifying passwords. The secondary administrator can manage the third-level administrator. User can log in to the system with a password, but the password cannot be changed. The third-level administrator can only log in to the system through the password. The user module interface is displayed in Figure 18.

10. Conclusion

Divided into hardware detection system and monitoring system software, this research was implemented with the idea of recognizing intrusions and intrusion types around the perimeter security system and designing the corresponding monitoring system software. The time-frequency characteristics were proposed for the vibration signal recognition. The first-level prejudgment of the intrusion events was made; then the EMD processing and Hilbert transform were used to obtain the time-frequency distribution of the signal. The time-frequency entropy and the center-of-gravity frequency were introduced and combined to the time-domain features to form the feature vector, which was input into multiclass model in the PNN for training and testing the data, thereby determining whether there is intrusion and generating the intrusion type. After multiple experiments when the detection range of the system is 10 km with the disturbance range of 1 km, it was discovered that the accuracy of event recognition is all above 95%, which means that the proposed method meets the queries of a good perimeter security system, with a probe response time of about 1.366 s.

The core function of the monitoring system is designed software according to the two-level vibration pattern recognition scheme proposed in this paper which is implemented on the LabWindows/CVI software development platform. The modular design and multithreading approach implemented in the software design result in an improved scalability and high efficiency of the system. The software has been successfully applied in Integrated Monitoring and Research Laboratory for Submarine Cable and Intelligent System of Shanghai Maritime University; the system has met the monitoring requirements. Even though the system

described in this paper can provide data query, information analysis, and technical decisions for the users, there are still some functions such as varying the temperature, strain, and altitude of the sensing cable columns that need to be addressed in future development. Once the development of these functions are completed, they will be integrated into the system; thereby forming a complete and performant perimeter security monitoring system.

Data Availability

The algorithms are the data used to support the findings of this study. They may be released upon application to the Integrated Monitoring and Research Laboratory for Submarine Cable and Intelligent System of Shanghai Maritime University.

Conflicts of Interest

The authors declare no conflicts of interest.

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