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INTELLECTUAL HARDWARE-SOFTWARE COMPLEX FOR FIBER-OPTIC SYSTEM MONITORING WITH CLASSIFICATION OF THE EVENTS AND RECOMMENDATIONS

Abstract: Currently, there are many different methods of monitoring extended facilities. However, the most accurate, efficient, and more accessible methods are using fiber-optic sensors. This study examines existing methods based on the application of optical time-domain reflectometry (OTDR). Data from three main databases, namely Web of Science, Scopus, and Google Scholar, were considered as existing solutions. Among the existing types, the possibility of using interferometers was also taken into account. However, such systems are expensive and very sensitive. At the same time, OTDR systems have huge disadvantages, such as the relatively low sensitivity of such systems, the closeness of the solution, and the lack of integration. However, all the disadvantages, except for the proprietarity, can be eliminated by using a neural network. Therefore, a system based on an open architecture is proposed with the possibility of application on new and already installed monitoring systems using a neural network for classification and an expert system for assessing the situation and recommendations for the implementation of restoration work. A universal intelligent hardware–software complex is proposed, which includes modules for signal preprocessing based on Fourier transform, statistical filtering using the three-sigma method, event classification, and interpretation. The suggested developed system enables noise suppression, event recognition (vibration, bending, cable breakage), and generation of recommendations through artificial intelligence. A convolutional neural network was used as a neural network for event classification. Recommendations and evaluation were provided using an expert evaluation module based on the use of Copilot, which reduces decision-making time and prevents possible breakdowns.

Keywords: fiber-optic sensors; Φ-OTDR; optical time-domain reflectometry; intelligent monitoring; power cable diagnostics; interferometer; signal processing; neural networks; machine learning; IoT architecture; predictive maintenance.

Introduction

Monitoring in technical systems and technological processes is an integral part of any enterprise or organization. At the same time, the main element of the monitoring system is both electromechanical and semiconductor sensors. Recently, fiber-optic [1] has become more

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widespread. Since the 1970s, optical conductors have been used as a sensing element capable of measuring temperature, mechanical stress, and impact force. Thus, sensors of this type have found application in the aerospace, energy, mining and security industries. Due to the increased sensitivity of the monitoring system, it has become possible to determine both strong physical impacts and minor ones that create damage. In turn, the properties of optical fiber also make it possible to measure the electrical parameters of the network, such as leakage current, voltage [1]. In comparison with existing solutions, fiber-optic systems have such advantages as immunity to electromagnetic interference, explosion and fire safety, and low power consumption. However, there are such disadvantages of such sensors as high sensitivity to mechanical stress.

In addition, there are currently many solutions for monitoring extended reinforced concrete structures, mining and mines. Therefore, the purpose of this work is to analyze trends in the application and development of fiber-optic monitoring systems. First of all, for the purposes of the study, the methods of bibliographic analysis of the main sources of literature in the field of fiber-optic sensors for monitoring the technical condition of power cables were used. Such scientometric databases as Web of Science, Google Scholar, Scopus were used as the most common. According to a full analysis of works from the Scopus database, the leading country in the study is China, which has 20166 works.

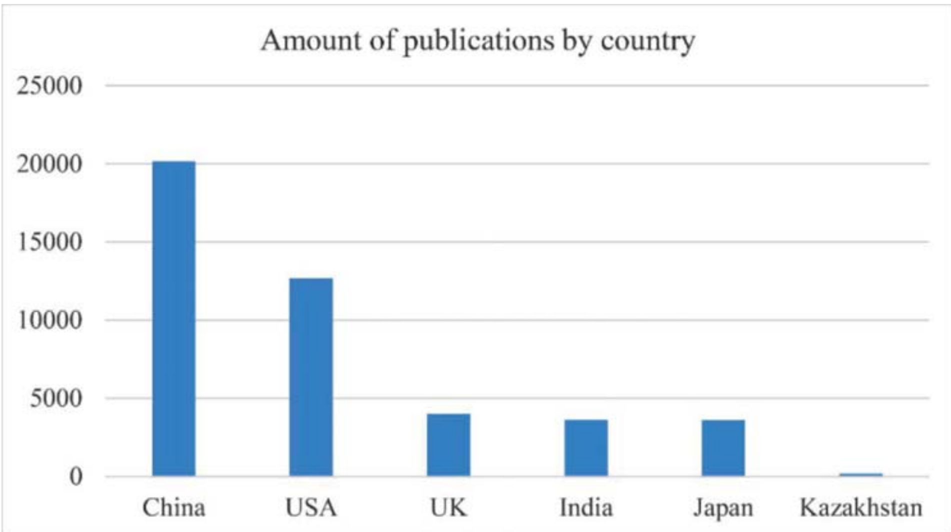

Figure 1. Histogram of the number of articles relative to other countries

The second and third leading countries are the US and the UK with 12,686 and 4,021, respectively, while the fourth and fifth are India and Japan with just over 3,600 surveys. In comparison with these countries, Kazakhstan with 193 papers in the Scopus database is more than 100 times behind China, and almost 18 times behind India and China (Fig. 2).

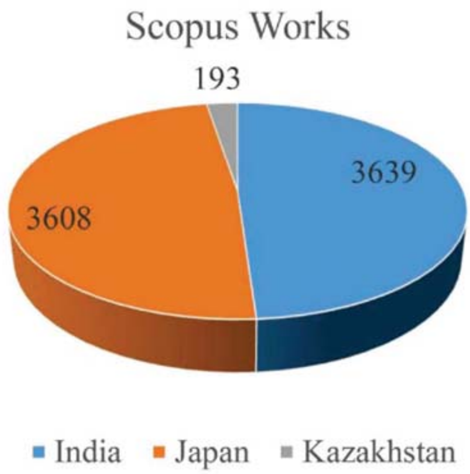

Figure 2. Pie chart comparing the number of articles in China, the USA, England and Kazakhstan

Fiber optic sensors have found their application in a variety of areas, however, the most interesting is for power cables. Therefore, this study is aimed at studying the current state of development of fiber-optic sensors to identify promising areas in problem solving.

At present, there are many solutions using OTDRs of various types. The most common method is the use of a phase-sensitive time domain reflectometer [2], [3], [4]. In general, the traditional scheme is used, which involves the use of a pulsed optical signal in the fiber-optic sensor circuit. For example, in [5], a similar system was used to study the state of power cable connections. Moreover, according to the demonstrated results of the experiment. In contrast to the previous solution, the paper [3] proposes the use of a fiber-optic sensor for measuring mechanical stress using a phase-sensitive optical time reflectometer. The algorithm is based on determining the intensity of Reilly's reflected light. The phase difference formed during the formation of an arc due to the mechanical impact exerted at a certain point of the cable. The system assembled according to this method differs in that it is received by a Mach-Zehnder interferometer (Figure 5). The advantage of the system is the accuracy of determination at long distances up to 10 km. In order to detect vibration sources, φ-OTDR can also be used in conjunction with the use of machine learning algorithms, which was proposed in [4]. Amplitude measurement for the signals of each frequency is performed using the Hilbert transform to process harmonics. The intelligent system then performs calculations based on the support vector method (SVM) architecture, as shown in Fig. 3.

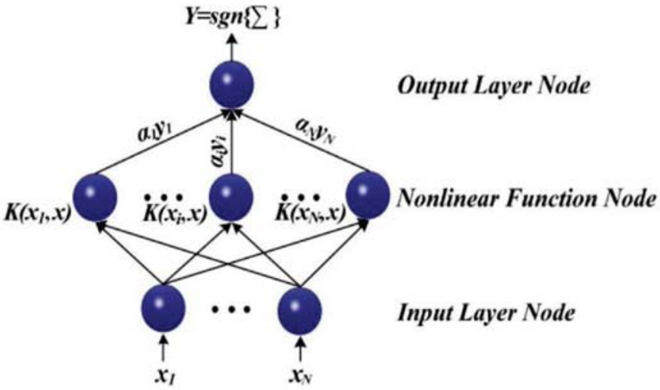

Figure 3. Structural diagram of information in the support vector method [4]

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The advantages are high accuracy, up to 97%, simplified design. The disadvantages are the complexity of the calculation and the narrow focus of the device.

On the other hand, a Sagnac interferometer can be used to measure partial discharges in power cables [5]. The analysis of the effects exerted on the optical fiber is carried out through the calculation of the phase difference, which is calculated due to the retained fiber (Fig. 4).

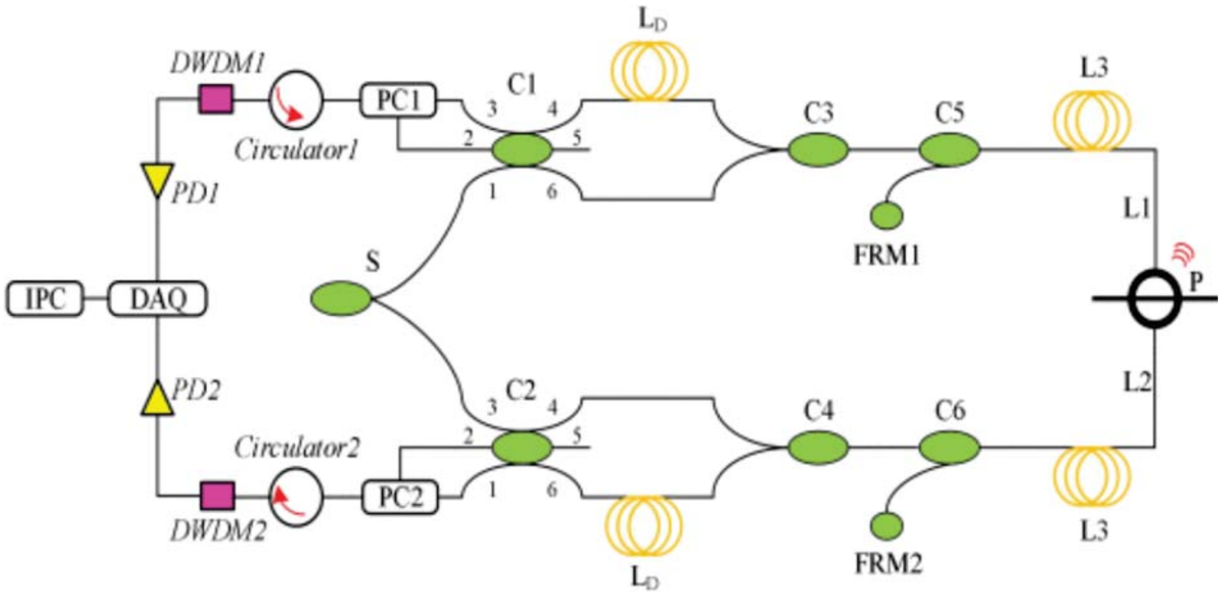

Figure 4. Structural diagram of the device with the Sagnac interferometer [5]

The advantages of this solution are measurement accuracy, selectivity, and increased sensitivity over long distances up to 6 kilometres. The disadvantages are the complex design and susceptibility to noise, the complexity of the measurement method.

A similar solution is the use of the Mickelson interferometer [6]. The method is based on determining the distance to the source of mechanical action by the phase difference using a piezoelectric element. The advantage is the high accuracy of determining the source of vibration caused by the discharge. The disadvantages are the complexity of the system, the high cost of components.

Another application of φ-OTDR has been found to determine the event that occurred by the intensity of light for each harmonic [7]. The proposed method is based on the transformation of the signal into the Gilbert space with the further transformation of the optimization problem into the Laplace space, which makes it possible to determine events by the signal-to-noise ratio (SNR). Classification is performed using the Linear Support Vector Machine (LSVM). The advantage of this solution is the achievement of high accuracy through the combined use of SNR and LSVM methods, however, this is also a disadvantage due to the complexity of the design and method of signal processing. It is also possible to use fiber-optic sensors to measure current for differential protection [8]. The principle of operation of the proposed device is based on the Faraday effect and was tested on generators to protect against internal damage to the stator and rotor. In general, the system provides reliable shutdown of a generator with a capacity of up to 300 MW with a sufficiently high sensitivity and provides a reduction in the protection response time. Among other things, methods based on hidden Markov models are also used to determine losses due to Rayleigh scattering [9]. In order to confirm the hypothesis, a dynamic model for time series recognition and data mining was also presented. In turn, this approach ensures accuracy in determining the type of impact, such as vibration, leakage, as well as other various mechanical effects. Based on the work [10], it can be noted that the most effective among all considered is the use of phase-coded coherent pulses with digital heterodyne demodulation, and the hybrid algorithm CNN-LSTM is used as an intelligent solution for event recognition. On the other hand, it is possible to organize a cloud-based IoT architecture for integration and adaptive learning.

In turn, the use of partial discharges in high-voltage cables using optical fiber using continuous online monitoring [11]. The study also considers the monitoring of the state of insulation and the prevention of failures in the energy infrastructure. Another such approach is [12], which also proposes the use of IoT architecture for online monitoring with distributed data collection and cloud analytics, providing remote analysis and failure forecasting. Thus, fiber-optic monitoring systems allow for accurate event detection based on φ-OTDR and FBG, providing the best spatial resolution and immunity to electromagnetic interference [13]. Moreover, the combination of φ-OTDR distributed sensors allows accurate measurement for a length of 80 km with an accuracy of 2-3 m [14]. In turn, it is possible to use Bragg grids for accurate measurements of mechanical effects [15].

It can also be noted that existing precision fiber-optic systems are proprietary and are not able to adapt to different cases, other solutions are point and do not allow monitoring the state of extended objects. On the other hand, existing systems do not consider classification of events and definitions of impact. And the new proposed systems cannot be adapted to already implemented systems.

The purpose of this study is to develop a universal system for intelligent analysis and signal processing from a fiber-optic monitoring system with further recommendations. Therefore, the solution under consideration is based on the use of open architecture [16], [17], [18].

Methods and Materials

In order to carry out the study, the main provisions of the theory of the magnetic field, machine learning, statistics, as well as mathematical analysis were used.

To perform the first task, which is to develop a module for processing and filtering the signal from excess noise, standard methods of primary analysis based on the Fourier method, performed by decomposing the graph into the sum of cosines and sines, were used.

The second task, which was further processing, required the application of a three-sigma statistical approach, which consisted in separating the obtained amplitudes into useful and noise by calculating the standard deviation.

The third task was to develop an AI intelligence module to adjust the values set for certain values and classify the event

Results

The system as a whole is comprehensive and can be used for various types of fiber-optic systems for monitoring the condition of power cables (Fig. 5.)

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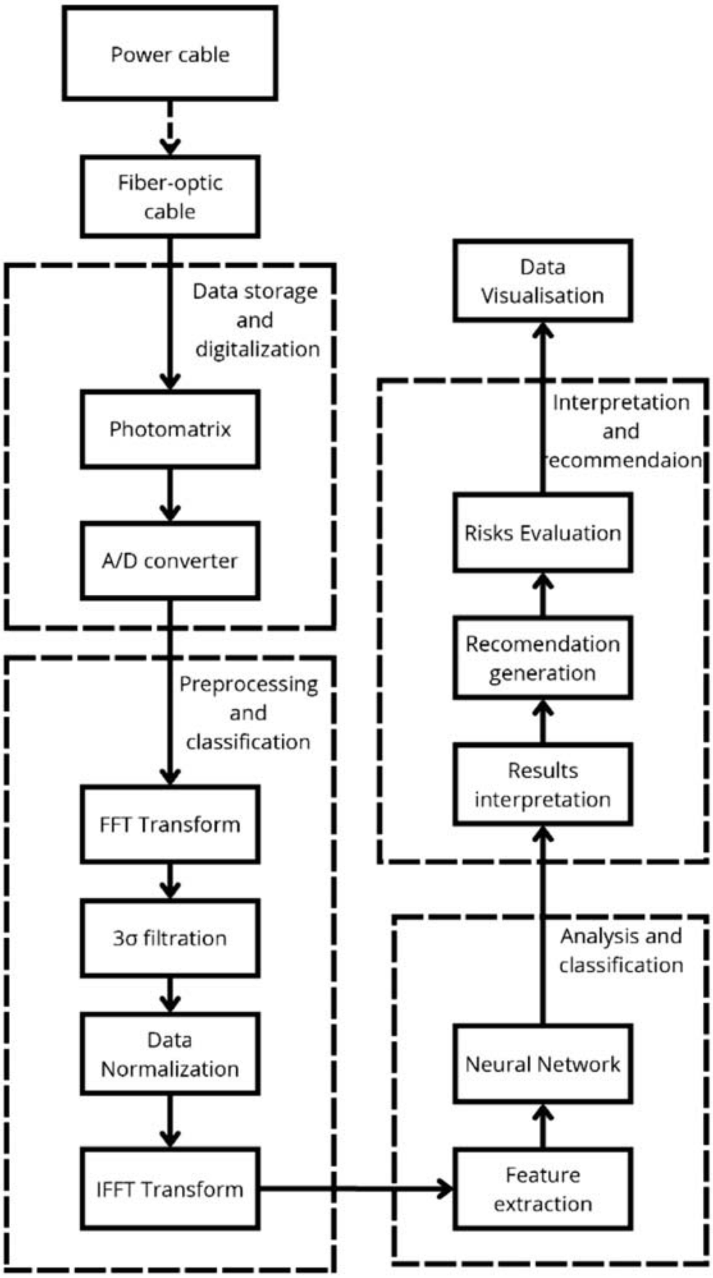

Figure 5. Conceptual model of the intellectual system

In this case, the fiber-optic cable acts as a sensitive element, and the mechanical impact on it changes the signal shape, which is tracked by the photomatrix. In this case, an ADC converter is used for signal processing, which in turn transmits the signal to a computing device containing preprocessing and classification, analysis and classification modules and an interpretation and recommendation module. The preprocessing process consists in calculating the amplitude based on the method of decomposition of the function into a number of cosines and sines:

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$$\begin{cases} a_n = \dfrac{1}{\pi}\displaystyle\int_{-\pi}^{\pi} f(t)\cos 2\pi nfdf; \\ b_n = \dfrac{1}{\pi}\displaystyle\int_{-\pi}^{\pi} f(t)\sin 2\pi nfdf, \end{cases} \quad (1)$$

where n is the harmonic number, f is the set operating frequency, $f(t)$ is the function of the reflectogram.

The amplitudes are then separated based on the three-sigma statistical method, thus removing the amplitudes of the noise harmonics based on the standard deviation

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(y(t_i) - y_m\right)^2}{n-1}}, \quad (2)$$

where y_m is the average value of the reflecotgram, i is the sequence number of the moment.

Then, if the harmonic amplitude is less than three sigmas, it is ignored, thus providing filtering.

After the initial filtering, data normalization is applied, providing data outlier cleanup, which makes it possible to determine events more accurately.

$$Y = \frac{y(x) - y_{\min}}{y_{\max} - y_{\min}}, \quad (3)$$

where $y_{\max}$ and $y_{\min}$ are maximum and minimum values in the reflectogram.

After normalization values, which do not lie in the interval from 0 to 1, are excluded and considered as outlier. Then, the Fourier transform allows to filter the signal to exclude noise:

$$f = \begin{cases} f_c, & \left|A_f(t) - A_{mf}\right| > \gamma\sigma_f \\ 0, & \left|A_f(t) - A_{mf}\right| < \gamma\sigma_f \end{cases}, \quad (4)$$

where $A_f(t)$ – function values for the selected frequency; γ – is the adjustable coefficient; σ_f – standard deviation for the frequency; A_{mf} – is the average value of the chosen frequency; f_c – cut frequency.

As a result, the inverse Fourier transform occurs with the remaining harmonics. The resulting value is then converted to extract features, which can be also displayed through the frequency, allowing the events to differ:

$$\begin{cases} f_s(n) = \sqrt{\dfrac{2}{\pi}}\displaystyle\int_{0}^{+\infty} A(x)\sin nxdx, \\ f_c(n) = \sqrt{\dfrac{2}{\pi}}\displaystyle\int_{0}^{+\infty} A(x)\cos nxdx. \end{cases} \quad (5)$$

The features are calculated through the classification by division of the reflectogram to determine the event. Namely, on the basis of a standard algorithm, anomalies in the reflectogram

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are identified and identified to study their impact. Then an artificial neural network is applied based on the method of calculating weight coefficients, which allows you to determine a specific event by separating strong pressure from vibration and breaks, bends.

$$\begin{cases} x_i = \left[A_f(z - L/2),\ \ldots,\ \mathrm{A}_f(z - L/2) \right]; \\ x_i^{(1)} = \mathrm{Re}\,LU(W_1 \cdot x_i + b_1); \\ x_i^{(2)} = \mathrm{Re}\,LU(W_2 \cdot x_i^{(1)} + b_2); \\ h_i = Flatten(x_i^{(2)}); \\ p_i = \mathrm{Soft\,max}(W_3 \cdot h_i + b_3); \end{cases} \tag{6}$$

where W_1, W_2, W_3 are weights for low, medium and high frequencies; b_1, b_2 are bias values.

The results of the neural network are then transmitted to an interpretation and recommendation module using Copilot and a query algorithm that allows you to determine the degree of impact of a certain impact, as well as to make a recommendation. The information is then transmitted in the form of a report and graphs to visualize the data.

The system module is presented on fig. 6.

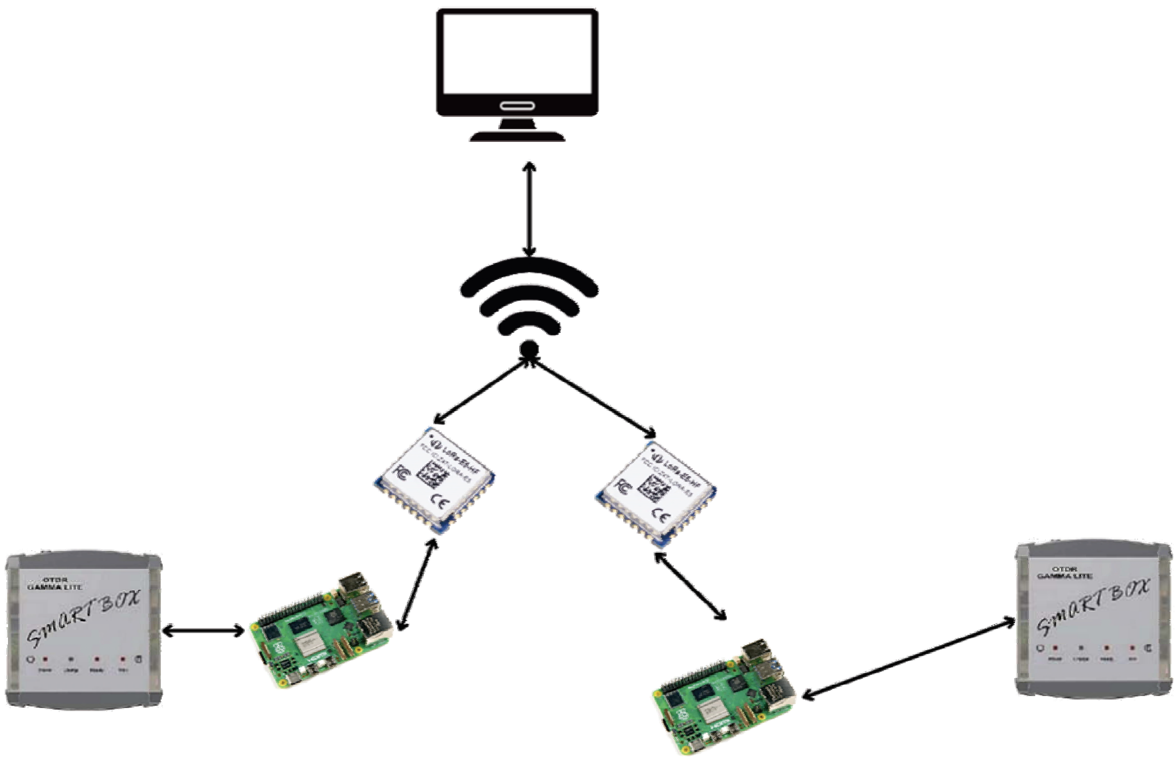


Figure 6. Implementation of the suggested model

In place of the main controller Raspberry Pi 4 was used and the sensor is SMARTBOX GammaOTDR Lite. All the calculations and the classification were done in frameworks of the Python based on OS of the Raspberry Pi 4. All data collected was sent to the cloud and then to the visualization with alert.

The real data is presented on the visualization program from the manufacturer (fig. 7) and values are imported in csv format file which are then converted into python for further processing.

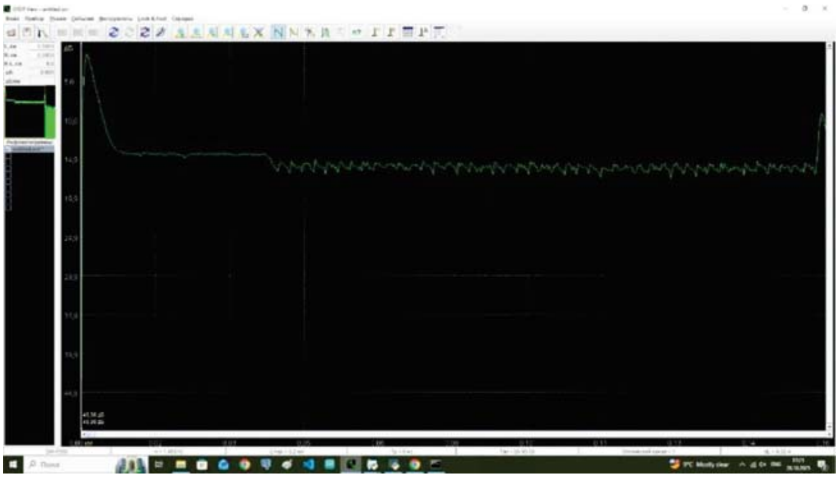
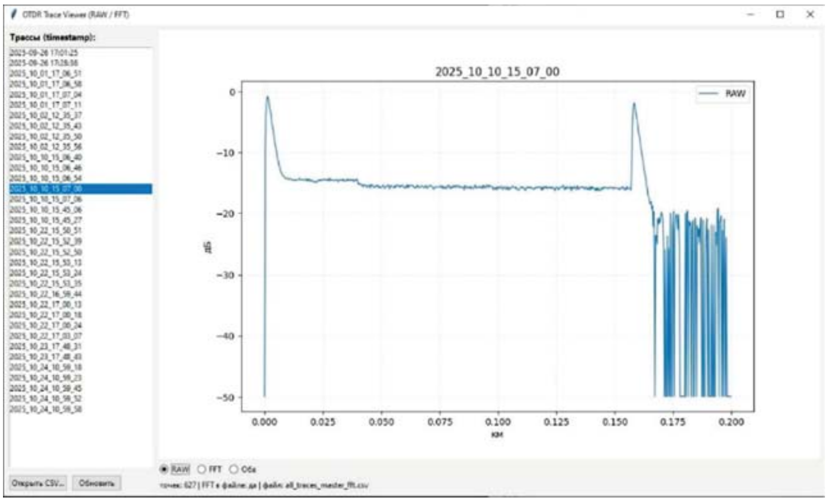
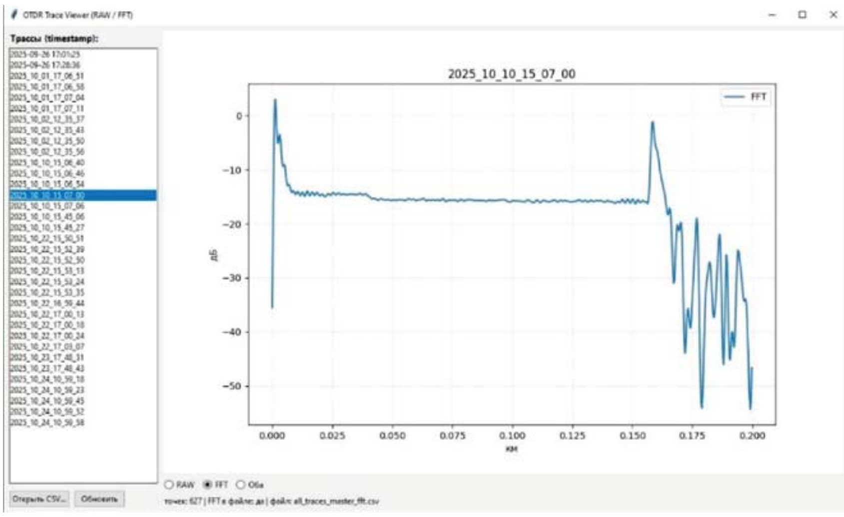


Figure 7. OTDR reflectometer values visualization

As a result, the OTDR Graphs are very clear and now allows to evaluate them clearly (fig. 8). In order to test the system different conditions were created for laboratory installations in order to achieve higher efficiency.



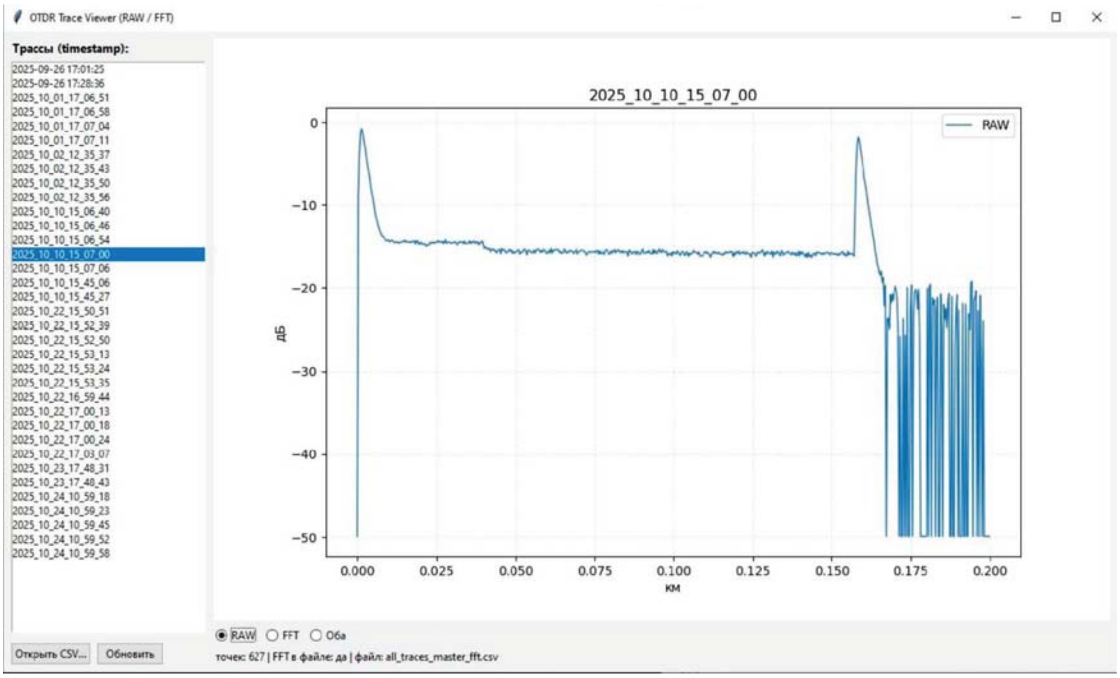
a



b

Figure 8. OTDR reflectometer values visualization of small impact:
a) actual; b) filtered

Other cases with different setting that were tested are demonstrated on fig. 9.



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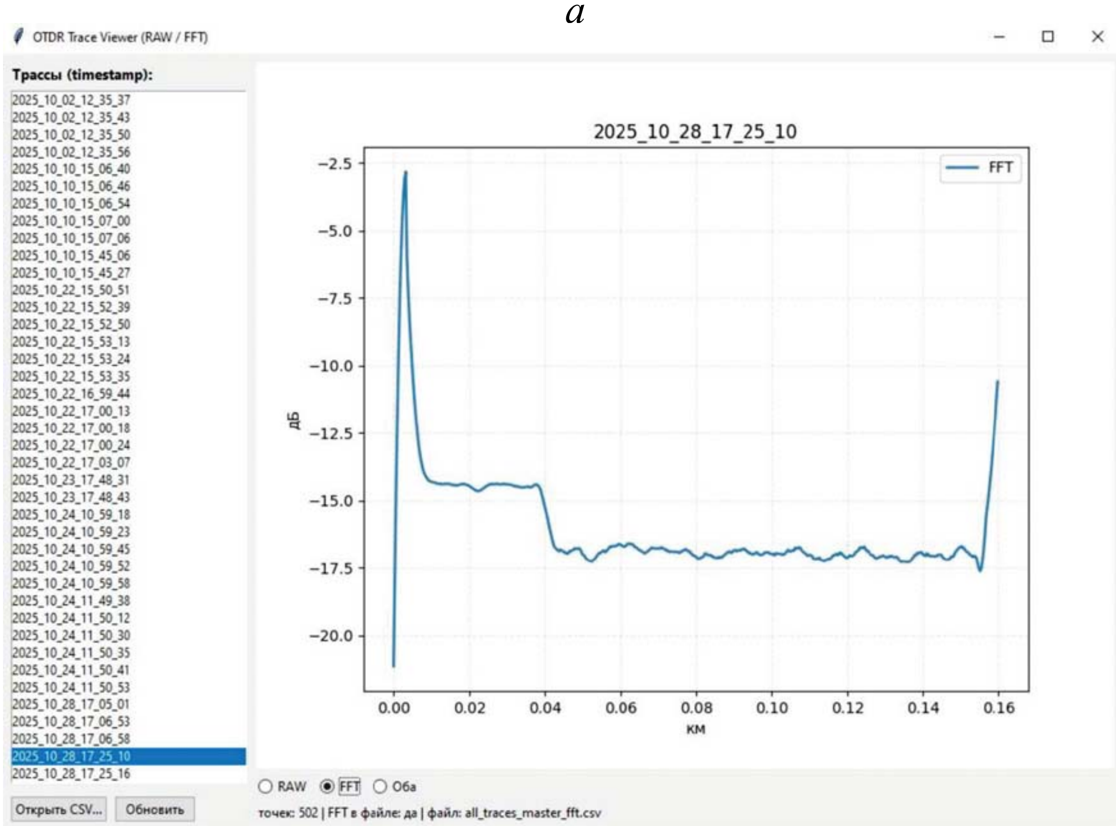

b

Figure 9. OTDR reflectometer values visualization of small impact:
a) actual; b) filtered

The change of the settings allows to evaluate the events clearly and with high precision determine what actually happened. Then the CNN were created to recognize the events (fig. 10).

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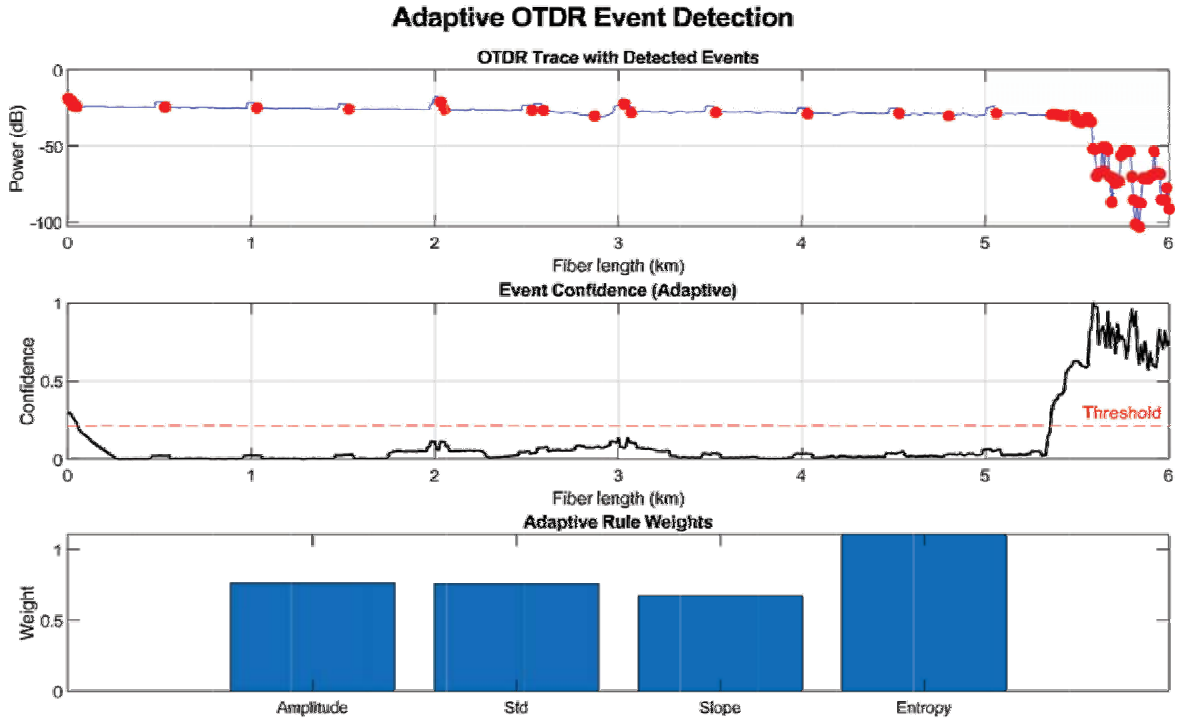

Figure 10. Implementation of the suggested model

The presented results on fig. 10 demonstrate that the CNN is possible to recognize the event, however confidence is low due to sharp drop in the end. Nevertheless, the information is sent to Copilot, which gives recommendations based on the data (Fig. 11).

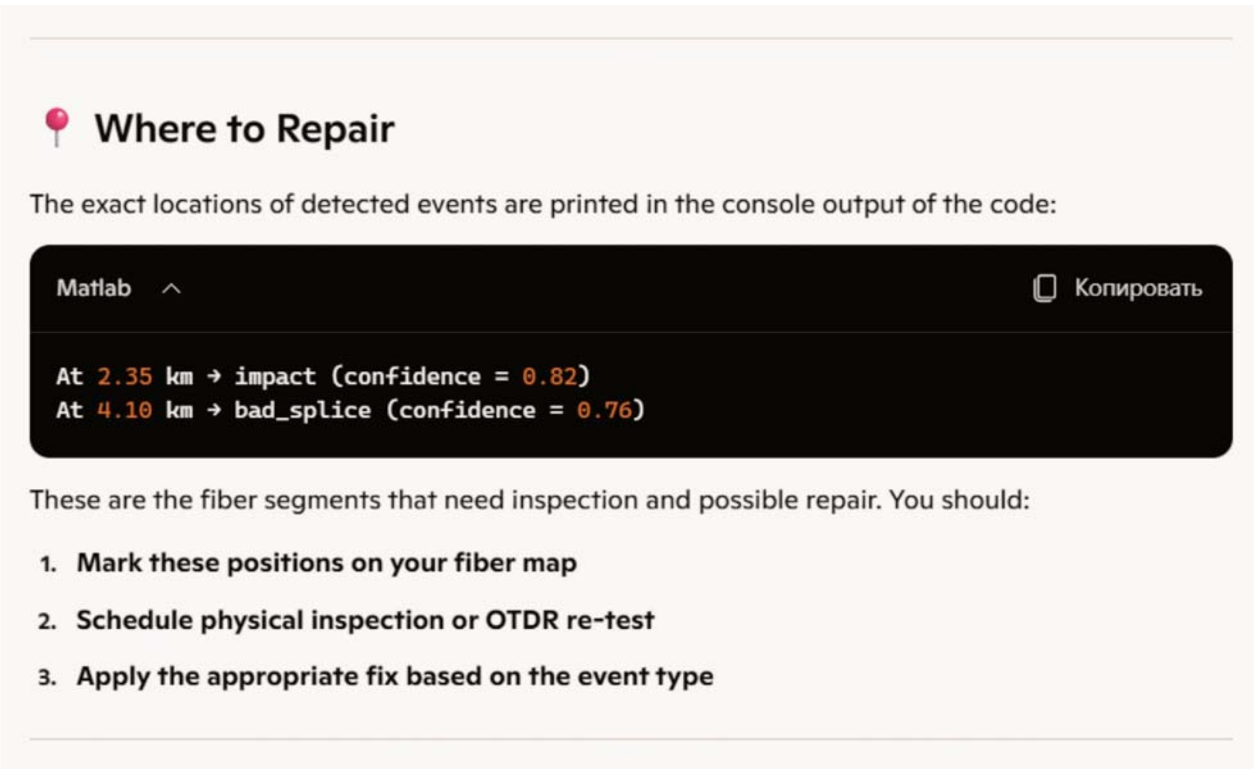

Figure 11. Implementation of expert module based on Copilot

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Discussion

The presented literature analysis demonstrates that currently there are many methods for monitoring the integrity of extended objects [1], [2], [3], [4], [5]. Among them, reflectometers stand out as the most accurate and less complex devices to develop, providing high accuracy in determining the impact site [9], [10]. However, one of the key problems remains their low sensitivity, which limits their effectiveness in conditions of weak or inconspicuous effects.

In this regard, the use of neural networks is being considered, which makes it possible not only to accurately identify the facts of exposure, but also to classify them by type and intensity. Hidden Markov models (HMM), convolutional neural networks (CNN), and long-term short-term memory (LSTM) networks are analyzed as such networks. However, according to the main results of the study, it is CNNs that demonstrate the highest accuracy, which justifies the choice of their use in the development of a monitoring system.

The classification of events was achieved through the integrated application of ten key features reflecting the characteristics of the signal, its spectral features and time parameters. This significantly improved recognition accuracy and reduced the number of false positives.

The system under development is versatile and can be integrated into both new solutions and existing monitoring systems based on fiber-optic sensors. This provides flexibility in implementation and expands the scope of the technology.

Conclusion

As a result of this study, the following results were achieved and the work performed.

1. The existing monitoring systems using fiber-optic sensors were reviewed, where the lack of open interfaces and the inability to integrate with existing versions were highlighted.

2. A structural model of an open intelligent hardware and software complex using artificial intelligence to provide event classification was proposed.

3. The possibility of using an expert assessment module for events that occurred at the site was considered, thus providing an opportunity to recommend the implementation of restoration of damaged areas and ensuring integrity.

References

[1] Udd, E., & Spillman, W. B. Jr. (2024DCT). Fiber optic sensors: An introduction for engineers and scientists (3rd ed.). John Wiley & Sons.

[2] Hicke, K., & Krebber, K. (2017). Towards efficient real-time submarine power cable monitoring using distributed fibre optic acoustic sensors. 2017 25th Optical Fiber Sensors Conference (OFS), 1–4. https://doi.org/10.1117/12.2267474

[3] Masoudi, A., Pilgrim, J. A., Newson, T. P., & Brambilla, G. (2019). Subsea cable condition monitoring with distributed optical fiber vibration sensor. Journal of Lightwave Technology, 37(4), 1352–1358. https://doi.org/10.1109/JLT.2019.2893038

[4] Fouda, B. M. T., Yang, B., Han, D., & An, B. (2021). Pattern recognition of optical fiber vibration signal of the submarine cable for its safety. IEEE Sensors Journal, 21(5), 6510–6519. https://doi.org/10.1109/JSEN.2020.3041318

[5] Liu, Z., Liu, X., Zhang, Z., Zhang, W., & Yao, J. (2020). Research on optical fiber sensor localization based on the partial discharge ultrasonic characteristics in long-distance XLPE cables. IEEE Access, 8, 184744–184751. https://doi.org/10.1109/ACCESS.2020.3028765

[6] Ma, G.-M., Zhou, H.-Y., Zhang, M., Li, C.-R., Yin, Y., & Wu, Y.-Y. (2019). A high sensitivity optical fiber sensor for GIS partial discharge detection. IEEE Sensors Journal, 19(20), 9235–9243. https://doi.org/10.1109/JSEN.2019.2925848

[7] Abufana, S. A., Dalveren, Y., Aghnaiya, A., & Kara, A. (2020). Variational mode decomposition-based threat classification for fiber optic distributed acoustic sensing. IEEE Access, 8, 100152–100158. https://doi.org/10.1109/ACCESS.2020.2997941

[8] Yang, G., Xu, Q., Wang, L., Liu, J., Liu, C., & Chen, D. (2021). Enhanced Raman distributed temperature sensor using a high Raman gain fiber. IEEE Sensors Journal, 21(24), 27518–27525. https://doi.org/10.1109/JSEN.2021.3124906
[9] Wu, H., Liu, X., Xiao, Y., & Rao, Y. (2019). A dynamic time sequence recognition and knowledge mining method based on the hidden Markov models (HMMs) for pipeline safety monitoring with Φ-OTDR. Journal of Lightwave Technology, 37(19), 4991–5000. https://doi.org/10.1109/JLT.2019.2926745
[10] Marie, T. F. B., Bin, Y., Dezhi, H., & Bowen, A. (2021). Principle and application state of fully distributed fiber optic vibration detection technology based on Φ-OTDR: A review. IEEE Sensors Journal, 21(15), 16428–16442. https://doi.org/10.1109/JSEN.2021.3081459
[11] Tian, Y., Lewin, P. L., Wilkinson, J. S., Schroeder, G., Sutton, S. J., & Swingler, S. G. (2005). An improved optically based PD detection system for continuous on-line monitoring of HV cables. IEEE Transactions on Dielectrics and Electrical Insulation, 12(6), 1222–1234. https://doi.org/10.1109/TDEI.2005.1561802
[12] Xu-Ze, G., Tianxin, Z., Ming, R., Bo, S., Wenguang, H., & Ming, D. (2019). IoT-based on-line monitoring system for partial discharge diagnosis of cable. 2019 IEEE Electrical Insulation Conference (EIC), 54–57. https://doi.org/10.1109/EIC43217.2019.9046569
[13] Khan, A. A., Malik, N., Al-Arainy, A., & Alghuwainem, S. (2012). A review of condition monitoring of underground power cables. 2012 IEEE International Conference on Condition Monitoring and Diagnosis, 909–912. https://doi.org/10.1109/CMD.2012.6416300
[14] Xinyun, W., Shuo, C., Liangliang, Y., Lei, C., & Huiying, W. (2020). Innovative practice of optical cable monitoring technology in the operation and maintenance of optical cables and transmission lines. 2020 International Conference on Wireless Communications and Smart Grid (IC-WCSG), 236–239. https://doi.org/10.1109/ICWCSG50807.2020.00059
[15] Fajkus, M., Martinek, R., Nazeran, H., Nedoma, J., Pinka, M., Koziorek, J., & Novák, M. (2021). Fiber-optic Bragg system for the dynamic weighing of municipal waste: A pilot study. IEEE Access, 9, 99050–99059. https://doi.org/10.1109/ACCESS.2021.3095219
[16] Neftissov, A., Sarinova, A., Kazambayev, I., Kirichenko, L., Kuchanskyi, O., & Faizullin, A. (2023). Determination of the speed of a microprocessor relay protection device of open architecture with a reed switch and the industrial internet of things. Eastern-European Journal of Enterprise Technologies, 2(5(122)), 20–30. https://doi.org/10.15587/1729-4061.2023.276588
[17] Neftissov, A., Biloshchytskyi, A., Andrashko, Y., Kuchanskyi, O., Vatskel, V., Toxanov, S., & Gladka, M. (2024). Evaluating the effectiveness of precision farming technologies in the activities of agricultural enterprises. Eastern-European Journal of Enterprise Technologies, 1(13(127)), 6–13. https://doi.org/10.15587/1729-4061.2024.298478
[18] Talipov, O., Kislov, A., Neftissov, A., Zvontsov, A., & Kirichenko, L. (2022). Metrological support of passive components of fiber-optical communication lines for determining the parameters of the effective length of a multi-mode tract taking into account dispersional characteristics. 2022 International Conference on Smart Information Systems and Technologies (SIST), 1–5. https://doi.org/10.1109/SIST54437.2022.9945740
[19] Yedilkhan, D., Neftissov, A., & Kusdavletov, S. (2022). The concept of an automated biotechnological filter for air purification. 2022 IEEE European Technology and Engineering Management Summit (E-TEMS), 175–178. https://doi.org/10.1109/E-TEMS53558.2022.9944442
[20] Neftissov, A., Biloshchytskyi, A., Novozhilov, A., & Kislov, A. (2021). Method for indirect measurement of the phase capacitance of a distribution substation and the single-phase earth fault current. IEEE EUROCON 2021 – 19th International Conference on Smart Technologies, 513–517. https://doi.org/10.1109/EUROCON52738.2021.9535640