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FIBER-OPTIC SENSOR–BASED PROACTIVE RAILWAY TRACK MONITORING USING VIBRATION ANALYSIS AND NEURAL NETWORKS

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The safety and efficiency of railway infrastructure directly depend on the integrity of the track infrastructure. However, transitional monitoring methods such as visual inspections, non-destructive testing, and track circuits are mostly reactive or periodic [1, 2]. They leave significant time intervals during which critical defects can appear and develop, while their effectiveness is limited by their scope, high cost, and vulnerability to external factors. This creates an urgent need for innovative, automated systems that are capable of providing continuous, high-precision, and most importantly, proactive monitoring of railway track conditions in real-time.

Under conditions of full-scale military aggression against Ukraine, the importance of such systems grows exponentially. Railway infrastructure has become a target, constantly subjected to attacks and sabotage aimed at disrupting military and humanitarian logistics. Traditional control methods are not effective enough at countering such threats; therefore, they need the immediate implementation of technologies that function as a system of continuous surveillance and instant response. They are capable of providing not only early warnings about the consequences of attacks, such as tracking damage caused by explosions, but also detecting attempts at physical interference by adversaries, including the installation of explosive devices or other sabotage objects.

This work proposes and theoretically substantiates an innovative approach that employs fiber-optic sensors (FOS), specifically the technology of distributed acoustic sensors (DAS), for monitoring railway infrastructure. The scientific novelty lies in the use of vibration and acoustic signals generated by the rolling stock itself to diagnose track conditions at a significant distance ahead of the train. This methodology transforms the train from a passive transport object into an active diagnostic tool that continuously “listens” to the path ahead. Instead of passively waiting for an event at the point of the sensor’s location, the system actively analyzes the propagation of energy emitted by the train within the rail structure. This allows proactive detection of rail integrity violations or the presence of foreign objects long before approaching them, providing critically important time to prevent emergencies.

The methodological basis of the system is the analysis of two key components of the vibration signal. First, rail integrity is assessed by analyzing the spatial attenuation of the transmitted wave. The presence of microcracks, fastening defects, or ballast degradation changes the physical properties of the rail, leading to a local increase in the attenuation coefficient. The DAS system, acting as a continuous array of virtual sensors, records an abnormally sharp drop in signal amplitude, accurately identifying a potentially damaged section. Second, the detection of foreign objects on the track is carried out through the analysis of reflected waves. An obstacle creates an acoustic impedance, reflecting part of the vibration energy to the source. The system identifies this "echo," and the propagation time makes it possible to precisely determine the distance to the object. Thus, one "natural" signal from the train is used to obtain two different types of diagnostic information: about distributed defects of the medium and about point obstacles.

The DAS technology generates enormous volumes of data, reaching terabytes per day, making manual analysis impossible. Therefore, a key, integral component of the proposed system is artificial intelligence and machine learning. The use of modern neural network architectures, such as convolutional neural networks (CNN) for recognizing unique patterns in signal spectrograms and long short-term memory (LSTM) recurrent networks for analyzing the temporal dynamics of events, makes it possible to automate the classification process. These models can, with high accuracy, distinguish vibrations from normal train movement, track defects, or external interference. AI in this context is not merely a tool for improvement but a fundamental technology that transforms arrays of raw optical data into structured, actionable information, without which the system cannot function [3].

In conclusion, the synergy of fiber-optic sensing technologies and advanced AI methods creates the foundation for transitioning from outdated reactive approaches to proactive and predictive management of railway infrastructure. Based on the neural network's conclusions, a practical algorithm for classifying the danger level has been developed, dividing the system's state into three levels—normal, warning, and critical. This makes it possible to generate clear, timely, and adequate alerts for operators and maintenance services, from scheduling technical inspections to the immediate suspension of traffic, which significantly enhances the safety, reliability, and economic efficiency of railway operations.

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