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Infrared Thermography for Diagnostics of Railway Infrastructure Elements

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Abstract

The paper presents research results on the application of infrared thermography for diagnostics of machines and devices in railway infrastructure. The theoretical foundations based on Fourier's heat conduction equation are outlined and the principles of designing an automated diagnostic system using thermal cameras, a data processing server, and machine learning algorithms are described. Examples of thermograms and graphs illustrate the detection of defects in cable connections, rail joints and turnout drives. Experimental studies confirmed that infrared diagnostics ensure high accuracy, speed and reliability in detecting hidden faults that remain unnoticed by traditional inspection methods. An economic analysis demonstrated a reduction in maintenance costs by up to 65% and a 67% decrease in train downtime. The obtained results prove the feasibility and effectiveness of implementing infrared thermographic systems in the maintenance practice of Ukrainian railways to enhance operational safety and optimize maintenance expenses.

Keywords: infrared thermography; railway infrastructure; diagnostics; non-destructive testing; thermal imaging camera.

1. Introduction

Infrared thermography (IRT) is a modern non-destructive testing (NDT) method that allows for the evaluation of surface temperature fields of objects in a non-contact manner. Its application in railway transport includes the diagnostics of turnout mechanisms, cable connections, rail joints, and signaling and interlocking (S&C) equipment.

In Ukraine, the relevance of this approach is determined by the high wear of infrastructure, the frequency of failures, and the insufficient level of automation in diagnostics [1], [2], [6]. The main purpose of implementing IRT is the timely detection of defects, reduction of emergency situations and optimization of maintenance costs.

International experience demonstrates that in the Federal Republic of Germany (Deutsche Bahn), infrared control is actively used to prevent overheating in drives and transformers; in Japan (JR East) – to monitor cable routes and high-speed switch mechanisms; and in the United States (Amtrak, BNSF) – to inspect the contact network and power cabinets [4], [8].

2. Analysis of literature and regulatory documents

The topic of infrared thermography is actively covered in international journals. In the Sensors journal, several review papers have been published that systematize the methods of passive and active thermography [6]. Infrared Physics & Technology presents studies on new algorithms for processing infrared camera signals [2]. IEEE Transactions on Instrumentation and Measurement highlights examples of practical applications in transport

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infrastructure [4], [5]. Additionally, standards such as ISO 18434-1, ISO 18436-7, and ASTM E1933 define the requirements for camera calibration, emissivity measurement, and interpretation of results [9], [10].

3. Purpose of the study

The main objective of implementing IRT is the timely detection of defects, reduction of emergency situations, and optimization of maintenance costs. The method combines speed, safety and high accuracy in identifying hidden defects, making it a promising tool for integration into automated control systems.

4. Theoretical background

The theoretical basis of infrared thermography is the Fourier heat conduction equation [1], [7]:

$$q = -\lambda \cdot \mathrm{grad}(T), \quad (1)$$

where q is the heat flux vector; λ is the thermal conductivity coefficient; $\mathrm{grad}(T)$ is the temperature gradient.

For railway elements (rail joints, cable connections), overheating can be estimated using the simplified formula [1], [7]:

$$\Delta T = (I^2 \cdot R \cdot t) / (m \cdot c), \quad (2)$$

where I is the current; R is the contact resistance; t is time; m is the material mass; c is the heat capacity.

Figure 1 shows an example of temperature field distribution modeling in a node with increased contact resistance.

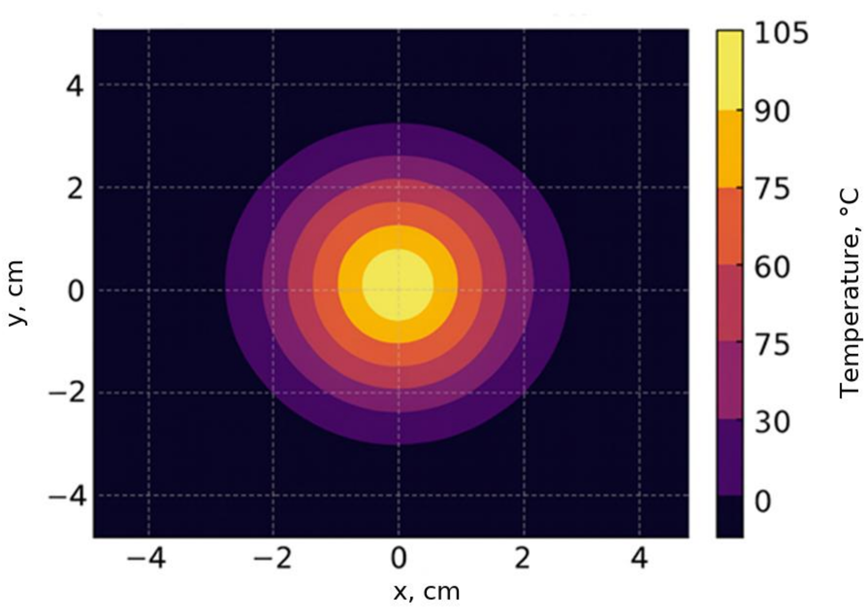

Fig. 1. Temperature field distribution.

5. Methodology

The proposed methodology involves constructing an automated diagnostic system consisting of a thermal imager, a preprocessing unit, a server, and machine-learning algorithms (see Table 1). The general workflow of the system is illustrated in Figure 2.

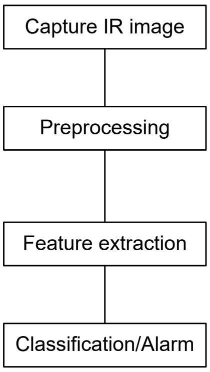

Fig. 2. Algorithm of the diagnostic system operation.

Table 1. Equipment used in the diagnostic system

Component	Model / Characteristics
Thermal imager	FLIR E95, 464×348 pixels, range −20…+650 °C
Optical lens	42° FOV
Server	Intel Xeon, 32 GB RAM, SSD 1 TB
Software	MATLAB, Python (OpenCV, TensorFlow)

6. Research results

Experimental measurements have demonstrated the effectiveness of infrared diagnostics for various objects of railway infrastructure. The obtained thermograms make it possible to detect hidden defects that cannot be identified using traditional methods.

In the thermogram (Fig. 3), localized areas of increased temperature can be observed, indicating the presence of thermal anomalies in the investigated unit. The maximum temperature in the center of the area reaches approximately 100 °C, while the peripheral region has a temperature of about 30 °C.

The color scale on the right illustrates the temperature range from 20 °C (violet tones) to 100 °C (yellow tones). The X-axis represents the geometric position of the element (mm), and the Y-axis shows the height coordinate (mm). Thus, the figure reflects the spatial temperature distribution on the surface of the object.

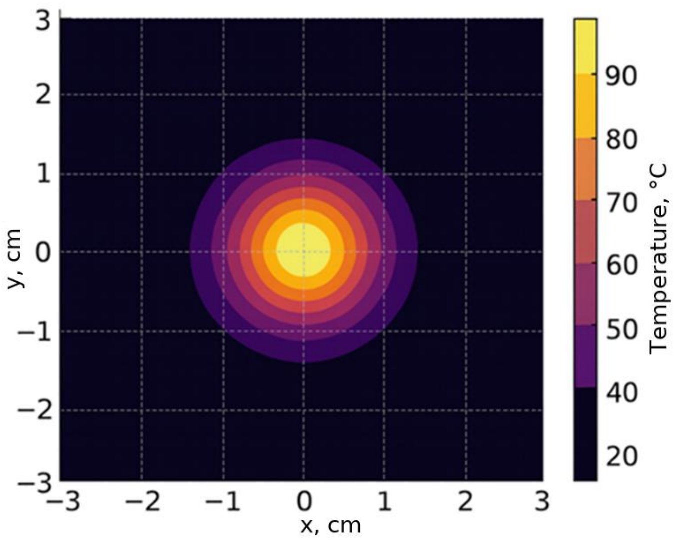

Fig. 3. Thermogram of cable connection.

In the thermogram, local overheating zones are visible, indicating increased contact resistance or insulation defects. Such areas are potentially hazardous and may lead to equipment failures.

The temperature–time dependence for the control point is shown in Fig. 4.

From the graph, it is evident that the temperature changes cyclically: during the first 20 minutes, heating up to approximately 40 °C is observed, followed by cooling down to about 15 °C, and then a subsequent rise again.

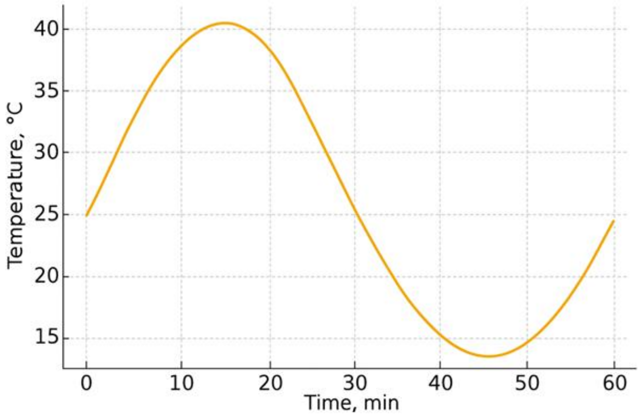

Fig. 4. Temperature vs time dependency during operational testing.

The temperature–time graph shows a gradual increase in the average temperature level with superimposed fluctuations. This indicates the presence of both periodic loads and a long-term trend toward overheating. A comparison of parameters for different objects is presented in Table 2.

Table 2. Comparison of parameters for different objects.

Object	Normal temperature, °C	Anomaly temperature, °C	Comment
Turnout mechanism	up to 40	60–80	Drive overheating
Cable connection	up to 35	55–70	Poor contact
Rail joint	up to 45	65–85	Increased resistance

7. Economic Effect

The results of the economic analysis are given in Table 3, and the graphical representation of the cost difference is shown in Fig. 5.

Economic analysis demonstrates a significant difference between traditional diagnostic methods and the implementation of infrared control [1], [2], [4]. Inspection costs are reduced by 2–3 times, while additional savings are achieved through decreased train downtime and fewer emergency repairs.

Table 3. Comparison of diagnostic methods and cost savings.

Parameter	Traditional methods	IR diagnostics	Savings
Average inspection cost per object (UAH)	2000	700	65 %
Inspection time per object	≈ 3 hours	10–20 min	–
Repair cost per object (UAH)	≈ 50 000	≈ 20 000	60 %
Train downtime due to failures (hours / year)	≈ 120	≈ 40	− 67 %

As shown in Table 3, the application of infrared diagnostics makes it possible to reduce the average inspection costs per object by 65%, decrease rolling stock downtime by more than 67%, and lower repair expenses by over 60%, providing a significant economic effect from the implementation of the method.

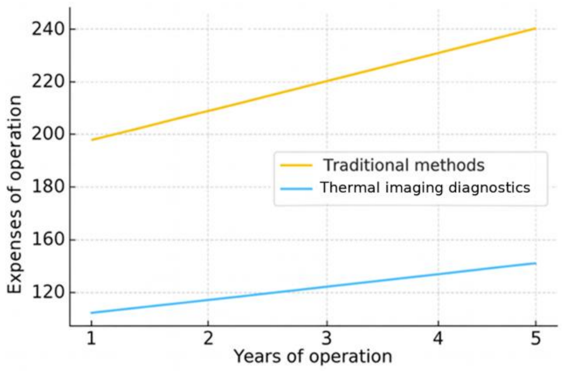

Fig. 5. Comparison of expenses of traditional methods and IR diagnostics.

8. Conclusion

This research substantiates the feasibility of using infrared thermography for the diagnostics of railway infrastructure elements. A methodology for developing an automated monitoring system has been proposed, experimental studies have been conducted, and an economic analysis has been performed.

Key findings:

- IR diagnostics provides high accuracy and speed in defect detection;
- The use of an automated system reduces maintenance and repair costs by 2–3 times;
- Implementation of the system enhances train safety and minimizes downtime;
- The results correspond to the international experience and can be adapted to Ukrainian conditions.

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Інфрачервона термографія для діагностики елементів залізничної інфраструктури

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Анотація

В статті представлено результати дослідження ефективності застосування інфрачервоної термографії для діагностики машин і пристроїв залізничної інфраструктури. Розкрито теоретичні основи методу, що базуються на рівнянні теплопровідності Фур'є та описано принципи побудови автоматизованої системи контролю з використанням тепловізійних камер, серверного модуля обробки та алгоритмів машинного навчання. Наведено приклади термограм і графіків, які ілюструють роботу системи під час виявлення дефектів у кабельних з'єднаннях, рейкових стиках і стрілочних переводах. Проведено експериментальні дослідження, результати яких підтвердили, що інфрачервона-діагностика забезпечує високу точність, швидкість обстеження та виявлення прихованих дефектів, недоступних для традиційних методів. Економічний аналіз засвідчив зниження витрат на обслуговування до 65 % і скорочення простоїв поїздів на 67 %. Отримані результати доводять доцільність впровадження інфрачервоних-технологій у практику технічного обслуговування українських залізниць.

Ключові слова: інфрачервона термографія; залізнична інфраструктура; діагностика; неруйнівний контроль; тепловізійна камера.