

MODERN NON-DESTRUCTIVE TESTING METHODS IN MONITORING DRIVE SYSTEMS OF BELT CONVEYORS: REVIEW AND COMPARATIVE ANALYSIS

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Abstract: The article presents a review of modern non-destructive testing (NDT) methods used for monitoring the technical condition of belt conveyor drive systems. The main diagnostic approaches are considered, including vibration diagnostics, thermal imaging inspection, analysis of electrical parameters of drive motors, acoustic emission methods, and intelligent monitoring systems based on machine learning and computer vision.

A comparative analysis of the capabilities of various NDT methods has been carried out in terms of their informativeness, sensitivity to early-stage defects, and applicability in industrial conditions. It is shown that vibration and electrical diagnostics provide the highest efficiency in continuous monitoring of drive units. In contrast, thermal imaging and visual inspection are advisable to use as part of integrated equipment condition assessment systems.

Particular attention is paid to modern approaches based on Motor Current Signature Analysis (MCSA) and signal processing methods using neural network algorithms. It is noted that integrating several diagnostic methods increases the reliability of defect detection and enables the transition to predictive maintenance.

Based on the review, developing multi-level monitoring systems that integrate electrical, vibration, thermal, and intelligent diagnostic methods is advisable to enhance the reliability and operational efficiency of belt conveyors.

Keywords: belt conveyor; non-destructive testing; technical condition monitoring; vibration diagnostics; motor current signature analysis (MCSA); predictive maintenance.

INTRODUCTION

Belt conveyors are a key component of modern transport and technological systems and are widely used in the mining, metallurgical, cement, agricultural, and logistics industries. Their application ensures continuous material handling over long distances, automates production processes, and enhances the overall efficiency of technological lines. Despite their high productivity and reliability, belt conveyors are associated with several technical



issues, primarily related to drive systems. The most common failures include bearing and gearbox wear, roller damage, belt deformation and slippage, increased vibration levels, and overheating of drive components. Such defects lead to unplanned downtime, reduced productivity, and increased maintenance costs. These problems are particularly pronounced in mining enterprises, where conveyors operate under conditions of increased dust levels, intensive abrasive wear, high humidity, and significant temperature fluctuations, which substantially affect equipment reliability (Windmann et al., 2018; Galkin & Sheshko 2017). According to operational statistics, up to 22% of all conveyor line downtime is caused by drive station failures. A significant share of maintenance costs is associated with the repair of rollers and gearboxes, whose share of the cost structure can reach 40% (Lagerev et al., 2026; Kuzin et al., 2024; Shandukh et al., 2024). Traditional inspection methods based on scheduled maintenance and visual examinations do not ensure timely detection of hidden defects and are increasingly insufficient in modern industrial production. In this regard, in recent years, non-destructive testing (NDT) methods have been actively developed, allowing the assessment of equipment condition without interrupting the technological process. The most common approaches include vibration diagnostics, thermal imaging inspection, analysis of electrical parameters of drive motors, acoustic emission methods, and monitoring systems based on intelligent data processing (Stempnyak et al., 2021; Goncharov, 2022). Recent studies demonstrate the significant potential of integrating multiple diagnostic methods to improve the accuracy and reliability of drive system condition assessments.

Methods based on Motor Current Signature Analysis (MCSA) are particularly important, as they enable early detection of conveyor malfunctions without the need to install additional sensors on mechanical components. An example of this approach is the Cross-Correlation of Stator Current Spectral Components Method version 3A (CCSM3A), which provides effective real-time diagnostics of belt misalignment (Kiselev & Kolobov, 2019). In parallel, methods using the short-time Fourier transform and CNN neural networks for the analysis of vibration and visual signals are being developed, enabling high-accuracy identification of damage to conveyor components. However, despite the wide variety of existing solutions, to date, no universal and comprehensive approach ensures reliable assessment of the technical condition of belt conveyor drive systems under real operating conditions. The differences among applied methods, their varying sensitivity to specific types of defects, and the particularities of industrial environments make selecting an optimal diagnostic strategy challenging.

These circumstances highlight the need to systematize modern non-destructive testing methods and analyze their practical capabilities and limitations. The present work aims to review and compare modern NDT methods for monitoring the technical condition of belt conveyor drive systems, and to evaluate their prospects for integration into predictive maintenance systems. The scientific novelty of this study lies in the authors' proposed conceptual framework for integrating electrical, vibration, thermal, and visual diagnostic methods into a unified predictive maintenance architecture. Unlike previous studies that mainly analyze individual diagnostic techniques separately, the proposed framework establishes a structured relationship between diagnostic data acquisition, machine-learning-based data fusion, condition assessment, and maintenance decision-making. Therefore, this framework represents the authors' own contribution and may serve as a methodological basis for developing intelligent predictive maintenance systems for belt conveyor drive units.

METHODOLOGY OF RESEARCH

The present study is a review aimed at systematizing modern non-destructive testing methods used for monitoring the technical condition of belt conveyor drive systems. To improve the transparency and reproducibility of the review process, the literature search and selection procedure were conducted according to the principles of the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [50]. The literature search was performed between January and March 2026 using the international scientific databases Scopus, Web of Science Core Collection, IEEE Xplore, ScienceDirect, SpringerLink, MDPI, IOPscience, and eLIBRARY.RU (RSCI). Additional publications were identified through references cited in review papers and conference proceedings related to conveyor diagnostics and predictive maintenance. The search strategy was based on combinations of keywords associated with belt conveyor systems, condition monitoring, non-destructive testing, fault diagnosis, predictive maintenance, vibration diagnostics, thermal imaging inspection, Motor Current Signature Analysis (MCSA), machine learning, and computer vision. Boolean operators AND and OR were used to refine the search results and identify the most relevant publications. Typical search queries included combinations such as “belt conveyor” AND “condition monitoring”, “belt conveyor” AND “non-destructive testing”, and “conveyor drive” AND “fault diagnosis”.

The review focused on publications published between 2017 and 2025, reflecting the period of intensive development of intelligent monitoring systems and predictive maintenance technologies. Only peer-reviewed journal articles and conference proceedings containing experimental, analytical, numerical, or industrial application results were considered. Publications not directly related to conveyor systems, studies lacking diagnostic content, conference abstracts, patents, dissertations, and non-peer-reviewed materials were excluded from further consideration. Following the initial database search, all retrieved records were exported to a reference management database. Duplicate publications identified across multiple databases were detected automatically and subsequently verified manually. In total, 864 records were identified through database searching. After the removal of 212 duplicate records, 652 publications remained for title and abstract screening. At this stage, 524 records were excluded as irrelevant to the scope of the review. The full texts of 128 articles were then assessed for eligibility. Of these, 68 publications were excluded because they were not directly related to conveyor diagnostics, lacked sufficient diagnostic or methodological content, or did not meet the inclusion criteria. As a result, 60 studies were finally included in the qualitative review. After duplicate removal, the remaining records were subjected to title and abstract screening, followed by full-text assessment to determine their relevance to the objectives of this review. Particular attention was given to studies describing practical implementations of vibration diagnostics, thermal imaging, electrical diagnostics, MCSA methods, machine learning algorithms, and intelligent monitoring systems for conveyor equipment. The quality of the selected sources was assessed according to the clarity of research objectives, adequacy of methodology, availability of experimental validation, industrial applicability, and scientific quality of the publication source. Preference was given to publications indexed in major international databases and published in peer-reviewed scientific journals.

The selected studies were subsequently analyzed and compared according to the diagnostic method employed, monitored conveyor component, operating conditions,

diagnostic sensitivity, advantages and limitations, and potential integration into predictive maintenance systems. This approach enabled a comprehensive assessment of the current state of research and identification of the most promising directions for the development of monitoring systems for belt conveyor drive units. To reduce selection bias, publications were additionally classified according to the diagnostic principle, monitored conveyor component, level of industrial validation, and applicability to predictive maintenance systems. This classification provided the basis for the comparative analysis presented in this review. The study identification, screening, eligibility assessment, and final inclusion process are summarized in Fig. 1 in accordance with the PRISMA 2020 framework.

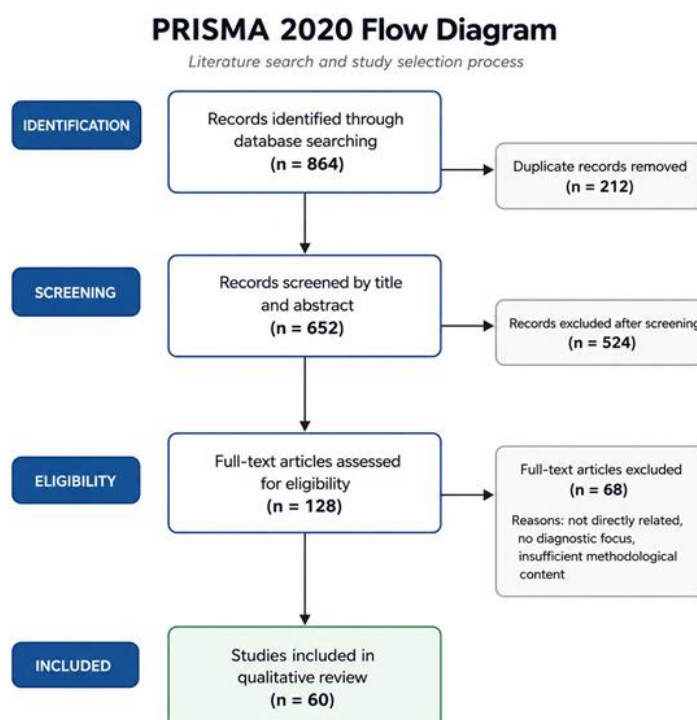


Fig. 1. PRISMA 2020 flow diagram of the literature search and study selection process

ANALYSIS OF THE DESIGN FEATURES OF CONVEYOR DRIVE SYSTEMS

The drive system of a belt conveyor comprises mechanical and electrical components that ensure torque transmission and stable belt movement under various operating conditions. The key drive elements with diagnostic significance include the electric motor, gearbox, drive drum, roller supports, bearing units, coupling devices, and braking systems (Fig. 2). The fundamental principles of calculation and design of these components are discussed in detail in specialized technical literature on conveyor equipment (Farhat et al., 2023). The electric motor, predominantly an asynchronous motor with frequency control, serves as the primary source of diagnostic information about the drive condition, as its current, temperature, and vibration parameters enable assessment of the technical condition of the entire drive unit. Analysis of the motor current signature, temperature profile, and load dynamics is widely used for the early detection of overloads, misalignments, and mechanical defects.

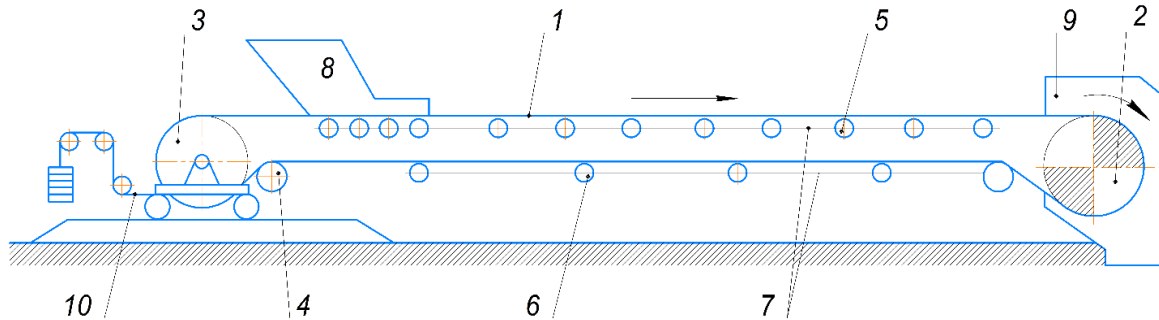


Fig. 2. Diagram of a horizontal belt conveyor

1 – belt; 2 – drive drum; 3 – tension drum; 4 – idler drum; 5 – upper roller supports; 6 – lower roller supports; 7 – frame; 8 – loading chute; 9 – guide trough; 10 – tensioning device

The gearbox, which converts rotational speed and torque, is one of the most heavily loaded and failure-prone components of the drive system. Wear of gears and bearings is accompanied by increased vibrations, localized overheating, and reduced efficiency, making the gearbox a primary target for vibration and thermal imaging diagnostics. The drive drum generates the traction force and directly affects belt tension. Issues such as slippage, eccentricity, and liner wear are reflected in changes in the vibration spectrum and the temperature distribution on the drum surface. Roller supports and their bearing units ensure stable belt movement; defects in these components are among the most common causes of failure and can be effectively detected using vibro-acoustic monitoring and infrared thermography.

Modern belt conveyors are predominantly equipped with single- and dual-drum asynchronous drives with frequency control, operating under variable load conditions (Zhang et al., 2022; Zhou et al., 2024; Kulikov et al., 2024; Nielsen et al., 2020). The efficiency and reliability of modern conveyor drives are also influenced by compliance with advanced electric motor efficiency standards and optimized drive-system design principles (Alberti & Troncon, 2021). For long, high-power conveyor lines, multi-motor and distributed drive systems are used, including direct-drive solutions with permanent magnets, which feature reduced vibration levels and a more uniform belt tension distribution (Yan, 2022; Ziborov & Mnatsakanyan 2022; Cun et al., 2022; Trufanov & Serjan, 2019). The dynamic stability of adaptive conveyor drives under varying operational loads has also been investigated, demonstrating the importance of drive control algorithms for maintaining reliable conveyor operation (Kosh et al., 2018). The use of intermediate drives, which helps reduce longitudinal stresses in the belt and increase the reliability of the transport system, is also considered a promising direction (Feng et al., 2019; Trufanov & Avksentyev, 2019; Voznyak, 2025). From a diagnostic perspective, the gearbox-motor assemblies, coupling devices, and damping elements are of greatest interest. Wear of couplings and increased backlash lead to increased torsional vibrations, which are effectively detected using vibration monitoring methods. The use of hydrodynamic couplings and frequency-controlled drives helps reduce starting loads; however, it requires continuous monitoring of the thermal conditions and operational parameters of the transmission components (Trufanov & Avksentyev, 2019; Voznyak, 2025; Justrov & Iliev, 2022). The analysis indicates that the design features of drive systems directly determine the selection and effectiveness of non-destructive testing methods. Electrical, vibration, and thermal imaging methods are the most informative for assessing the condition of electric motors, gearboxes, drums, and bearing units. This

confirms the need for a diagnostic-oriented approach in the design and operation of belt conveyor drives.

MODERN NON-DESTRUCTIVE TESTING METHODS

Modern non-destructive testing (NDT) methods for belt conveyor drive systems are a key tool for ensuring equipment reliability under high-dust, high-vibration, and dynamic-load conditions. The specific operation of electric motors, gearboxes, couplings, drive drums, and bearing units requires diagnostic methods that can operate under working conditions without stopping the equipment or disassembling it. Several studies emphasize that the highest diagnostic effectiveness is achieved through the integration of multiple NDT methods, as each reflects only certain physical processes occurring within the drive system (Shandukh et al., 2024).

Visual inspection and measurement remain fundamental methods for detecting surface defects in metal structures, fasteners, welds, and belt components. Its main advantages are ease of implementation, speed, and minimal equipment requirements. Recent developments include mobile robotic inspection systems equipped with cameras and sensors that automate conveyor diagnostics in mining environments and reduce human involvement in hazardous areas (Shrek et al., 2022). However, the diagnostic capabilities of this method are limited by subjectivity in assessment, dependence on personnel qualifications, and low sensitivity to hidden and early-stage damage, which significantly reduce its effectiveness in monitoring the condition of critical components (Trufanov & Serjan, 2019). Thermal imaging inspection is widely used to diagnose gearboxes, bearings, and drive drums by analyzing temperature fields. The method is characterized by high speed, safety, and the ability to examine equipment during operation remotely. At the same time, its sensitivity depends on the presence of pronounced thermal anomalies, so early-stage defects that do not cause noticeable overheating may remain undetected. In addition, measurement results are significantly influenced by external temperature conditions and equipment operating modes (Liu et al., 2021; Rami, 2023).

Vibration diagnostics is one of the most sensitive and informative methods for assessing the condition of mechanical drive components. Analysis of vibration spectra, time-domain signals, and envelope signals enables the detection of imbalance, shaft misalignment, loosened fasteners, gear wear, and bearing defects at early stages of development. High sensitivity and the ability to quantitatively assess component condition make vibration diagnostics a primary tool for condition-based maintenance. At the same time, its practical application requires proper sensor placement, stable measurement conditions, and qualified interpretation of the obtained data (Windmann et al., 2018; Shimasaki et al., 2021; Afonso Bowler, et al 2024; Yundre, 2019). Analysis of operational materials, primarily gearbox lubricating oils, provides additional information on wear, contamination, and overheating of internal components. Determining the content of wear products, changes in viscosity, and chemical composition allows indirect assessment of the condition of gears and bearings. This method is simple to implement and effective for oil-filled units; however, it does not allow precise localization of defects and is therefore primarily used as part of comprehensive diagnostic programs (Kuzin, 2025).

Electrical diagnostic methods, including Motor Current Signature Analysis (MCSA), are among the most advanced directions in NDT. Specialized motor condition monitoring systems have also been proposed for coal-mine conveyor applications, enabling continuous supervision of drive performance and fault detection (Boslovyak & Tolkachev,

2019). Their key advantage is that they do not require physical access to mechanical components and allow for continuous online monitoring. Current spectrum analysis enables the detection of both electrical and mechanical defects, including rotor damage, phase asymmetry, eccentricity, bearing and gear wear, belt slippage, and drum misalignment. At the same time, these methods are sensitive to power supply quality and require specialized signal filtering and processing algorithms (Pediredla et al., 2024; Yang, 2024; Xi, 2024; Wang, 2024). Intelligent diagnostic methods based on machine learning, big data analysis, magnetic and vibroelectric sensors, and on-device anomaly detection algorithms significantly expand the capabilities of traditional NDT methods. Recent studies have also focused on integrated monitoring and control systems for conveyor electric drives, combining diagnostic information with automated control functions (Li, 2023). These approaches provide high accuracy in detecting hidden defects, automate data interpretation, and enable the prediction of the remaining service life of drive components. However, their practical implementation requires the accumulation of representative datasets, model training, and integration with the enterprise's digital infrastructure (Blazej et al., 2025; Kozhubaev et al., 2025; Khalifa et al., 2024).

A comparative analysis of the NDT methods reviewed shows that vibration and electrical diagnostics have the highest sensitivity to early-stage defects, visual and thermal inspection are distinguished by ease of industrial implementation, and oil analysis and intelligent methods are most effective as part of integrated monitoring systems. A significant limitation of most methods is their selectivity regarding the type of defect and the component being diagnosed, which precludes obtaining comprehensive information with a single method. Summary characteristics and areas of effective application of NDT methods are presented in Table 1.

Table 1. Comparative characteristics of NDT methods for belt conveyor drive system monitoring

NDT method	Main diagnostic parameter	Operating mode	Detectable defects / monitored conditions	Supporting sources
Visual inspection and computer vision	Images of belt surface and drive components	Periodic or online inspection	Belt surface damage, visible defects, misalignment, structural abnormalities	(Shrek et al., 2022; Blazej et al., 2025; Kozhubaev et al., 2025; Khalifa et al., 2024)
Thermal imaging monitoring	Temperature field and local thermal anomalies	Online or periodic monitoring	Overheating of bearings, gearboxes, drums, friction zones, lubrication problems	(Stempnyak et al., 2021; Goncharov, 2022; Shurgach et al., 2021; Liu et al., 2021)
Vibration diagnostics	Time-domain and frequency-domain vibration signals	Periodic or continuous monitoring	Imbalance, shaft misalignment, bearing wear, loosened fasteners, gear defects	(Stempnyak et al., 2019; Khalifa et al., 2023; Shimasaki et al., 2021; Bowler et al., 2024; Hills, 2024)
Motor Current Signature Analysis (MCSA)	Stator current spectrum and current-derived features	Continuous online monitoring	Belt misalignment, rotor defects, eccentricity, electromechanical	(Farhat et al., 2023; Pediredla et al., 2024; Zhang et al., n.d.;

			anomalies, load-related faults	Boslovyak & Tolkachev, 2019)
Acoustic and vibro-acoustic monitoring	Acoustic, thermal-acoustic, or vibro-acoustic features	Periodic or continuous monitoring	Abnormal friction, fatigue-related changes, tension-related faults, early fault symptoms	(Liu et al., 2021; Khalifa et al., 2023)
Lubricating oil analysis	Wear particles, viscosity, contamination, degradation products	Periodic inspection	Gearbox wear, bearing degradation, lubrication deterioration, contamination	(Bortnovski et al., 2022)
Intelligent diagnostic methods	Machine learning, data fusion, anomaly classification	Online monitoring and predictive diagnostics	Complex anomalies, automated fault classification, predictive maintenance decision support	(Wang et al., n.d.; Blazej et al., 2025; Kozhubaev et al., 2025; Khalifa et al., 2024; Li & Zhang, n.d.)

The characteristics summarized in Table 1 were selected only when they were directly supported by the cited literature or could be consistently derived from the reviewed studies. General NDT methods that were not sufficiently represented in conveyor-drive monitoring literature were excluded from the comparison to avoid unsupported generalization. Thus, none of the existing non-destructive testing methods provides a complete and comprehensive assessment of the technical condition of belt conveyor drive systems. The most effective approach is to integrate visual, thermal, vibration, electrical, and intelligent methods into a unified diagnostic system. This comprehensive approach increases reliability in assessing equipment condition, reduces the risk of unexpected failures, and enables a transition to condition-based maintenance and predictive equipment management. Industrial experience confirms that condition monitoring programs significantly reduce unexpected conveyor downtime and improve maintenance planning efficiency (Nielsen et al., 2020).

METHODOLOGY FOR MONITORING TECHNICAL CONDITION

In modern scientific publications, the monitoring of the technical condition of belt conveyor drive systems is considered a comprehensive process that combines non-destructive testing methods, including Motor Current Signature Analysis (MCSA), vibration diagnostics, and thermodiagnosics, and their integrated application. It is emphasized that the type of drive, operating conditions, level of enterprise automation, and the required depth of diagnostic information determine the choice of a specific monitoring methodology. One of the most promising directions is the use of methods for analyzing the electrical parameters of the drive motor. In (Farhat et al., 2023), an approach is described based on spectral analysis of current signals using the CCSM3A algorithm. This method is shown to detect conveyor belt misalignment with high reliability under both idle and loaded operating conditions. A significant advantage of this approach is the ability to perform real-time diagnostics without installing additional sensors on mechanical components.

Advanced variants of current signal analysis based on current-derived diagnostic features have also been discussed in the literature, allowing quantitative assessment of belt deviation and load-related changes (Pediredla et al., 2024; Zhang et al., n.d.). It was found that as belt deviation increases, this parameter increases proportionally, enabling a

quantitative assessment of defect severity while accounting for load variations. Such methods integrate well into automated monitoring systems and enable continuous equipment condition monitoring. Vibration diagnostics is considered a fundamental method for assessing the technical condition of mechanical components of the drive station and roller supports (Stempnyak et al., 2019; Khalifa et al., 2023; Shimasaki et al., 2021; Bowler et al., 2024; Hills, 2024). Analysis of vibration signals over a wide frequency range enables the detection of bearing wear, shaft misalignment, imbalance, and gear defects at early stages of development without disassembling the equipment. High repeatability of results and the ability to detect initial forms of mechanical degradation are emphasized when measurements are properly organized. Thermodiagnosics is used as an additional means of monitoring the condition of gearboxes, bearings, and rollers by analyzing temperature anomalies. The use of infrared sensors and thermal imaging systems enables the detection of localized overheating zones associated with increased friction, lubrication issues, and wear. The literature emphasizes that the informativeness of this method increases significantly when combined with vibration and electrical diagnostics.

Analysis of scientific publications shows that the highest monitoring effectiveness is achieved by combining MCSA, vibration, and thermal diagnostics. Studies (Blazej et al., 2025; Kozhubaev et al., 2025) note that such integrated systems allow simultaneous monitoring of electrical, dynamic, and thermal parameters of the drive system, providing a more comprehensive assessment of its technical condition and improving the reliability of diagnostic conclusions.

A comparative analysis of the literature indicates that methods based on spectral analysis of current signals demonstrate high sensitivity in detecting belt misalignment; integral electrical parameters account for the influence of operational load; and vibration and thermal diagnostics provide reliable identification of mechanical degradation in components. Together, these approaches form the basis for implementing continuous monitoring and transitioning to condition-based maintenance. Thus, the monitoring methodologies reviewed in this study confirm the feasibility of using combined non-destructive testing systems to enhance the reliability and predictability of belt conveyor drive system operation. The integration of electrical, vibration, and thermal methods into a unified diagnostic platform is considered the most promising direction for the development of modern maintenance systems.

ANALYSIS OF THE EFFECTIVENESS OF MODERN DIAGNOSTIC METHODS

The review of scientific publications shows that methods for monitoring belt conveyor condition are developing along two main directions: analysis of the electrical parameters of the drive motor (MCSA) and the use of computer vision technologies for visual inspection of the belt and drive components. The most promising results are achieved when these methods are used in combination. Approaches based on the analysis of stator electrical signals, particularly the CCSM3A spectral method, demonstrate high effectiveness in early detection of belt misalignment and drive system malfunctions. These methods are characterized by high diagnostic reliability and do not require installing additional sensors on mechanical components, making them economically feasible and convenient for industrial implementation. In recent years, computer vision methods based on YOLO-family neural networks have seen significant development. These methods provide high accuracy and speed in detecting visual defects in conveyor system

components. For example, the YOLOv5 architecture combined with the Grad-CAM algorithm achieves defect localization accuracy of up to 99% at a processing speed of 67.7 frames per second. Modern computer-vision models, including DFTNet and lightweight YOLO-based architectures, demonstrate high defect-detection accuracy and real-time processing capability, with reported values such as ACC = 99.48%, mIoU = 91.08%, mAP@0.5 = 98.74%, and processing speed up to 63.62 FPS [39,41]. For YOLOv5 combined with Grad-CAM, defect localization accuracy of up to 99% and a processing speed of 67.7 FPS have been reported [40]. Lightweight neural network architectures, such as GES-YOLO, are designed for edge device operation, enabling real-time monitoring even with limited computational resources.

Analysis of the literature shows that the highest diagnostic effectiveness is achieved by combining MCSA and computer vision methods. Electrical methods enable the detection of defects at early stages of development, while visual models provide accurate localization and quantitative assessment of damage to the belt and its structural components. At the same time, practical studies dedicated to integrating these approaches into a unified industrial monitoring system are currently very limited (Kuzin, 2023; Kuzin et al., 2025).

Existing research reveals several scientific and practical gaps. Only studies reporting clearly identifiable diagnostic methods, input data, validation procedures, and quantitative or qualitative performance indicators were included in Table 2. Most studies investigate diagnostic methods independently, whereas industrial applications require integrated multi-sensor monitoring systems capable of combining electrical, vibration, thermal, and visual information. Publicly available datasets for conveyor diagnostics remain limited, making objective comparison of machine learning models difficult. Furthermore, most studies are conducted under laboratory conditions and do not fully account for industrial factors such as dust, vibration, illumination variability, electromagnetic interference, and fluctuating loads. Limited attention has also been paid to data fusion strategies, explainable artificial intelligence, remaining useful life prediction, and maintenance optimization, which remain important challenges for future predictive maintenance systems.

Table 2. Extended comparative analysis of conveyor drive diagnostic methods

Study	Method	Dataset / sample size	Equipment / input data	Validation procedure	Main results
(Farhat et al., 2023)	MCSA using CCSM3A	Experimental conveyor drive dataset	Stator current signals and data acquisition system	Validation under idle and loaded operating conditions	Early detection of belt misalignment; localization accuracy approximately ± 0.5 mm
(Blazej et al., 2025)	YOLOv5 + Grad-CAM	Conveyor belt defect image dataset	RGB image data / industrial camera	Training and testing dataset split	Defect localization accuracy up to 99%; processing speed 67.7 FPS
(Wang et al., n.d.)	DFTNet	Industrial conveyor image dataset	Vision-based monitoring platform	Benchmark comparison with existing models	ACC = 99.48%; mIoU = 91.08%

(Kozhubaev et al., 2025)	GES-YOLO	Conveyor inspection dataset for edge-device deployment	Embedded edge-computing platform	Real-time testing and validation	mAP@0.5 = 98.74%; FPS 63.62
(Khalifa et al., 2024)	Sensor-based conveyor belt diagnostics	Sensor-based monitoring data	Sensor monitoring system	Review and comparative assessment of diagnostic approaches	Demonstrates the relevance of sensor-based diagnostics for preventive and predictive maintenance

The data presented in Table 2 confirm that computer vision methods achieve high accuracy and image processing speed. In contrast, electrical MCSA methods offer early defect detection without the need for additional sensor equipment. The most promising approach is their integration within a unified diagnostic platform.

Promising directions for further research include the development and testing of integrated diagnostic systems based on MCSA and computer vision methods, the creation of industrial datasets for model training and validation, and the optimization of algorithms for operation on edge devices capable of implementing predictive monitoring functions and automated decision-making.

FRAMEWORK FOR THE SELECTION AND INTEGRATION OF DIAGNOSTIC METHODS IN PREDICTIVE MAINTENANCE SYSTEMS

Based on the comparative analysis of modern non-destructive testing methods, a conceptual framework for selecting and integrating diagnostic techniques into predictive maintenance systems for belt conveyor drive units is proposed. Figure 3 illustrates the proposed conceptual framework for integrating Motor Current Signature Analysis (MCSA), vibration diagnostics, thermal monitoring, and computer vision into a unified predictive maintenance system for belt conveyor drive units.

As shown in Fig. 3, the proposed framework is organized as an integrated diagnostic structure. MCSA is used for continuous online screening of electrical and electromechanical anomalies, while vibration diagnostics and thermal monitoring provide detailed assessment of mechanical faults, overheating, and degradation of drive components. Computer vision supports the detection and localization of visible belt and surface defects. The diagnostic information obtained from these methods is combined through machine-learning-based data fusion, enabling condition assessment and predictive maintenance decision-making.

The scientific novelty and original contribution of this review lie in the authors' proposed classification and integration framework, which combines electrical, vibration, thermal, and visual diagnostic methods according to monitored components, defect criticality, and predictive maintenance requirements. Unlike previous reviews that mainly summarize existing approaches, the proposed framework establishes practical relationships between diagnostic methods and maintenance decision-making processes. Unlike conventional approaches that utilize individual diagnostic methods independently, the proposed framework combines electrical, vibration, thermal, and visual diagnostic information according to the type of monitored component and defect severity.

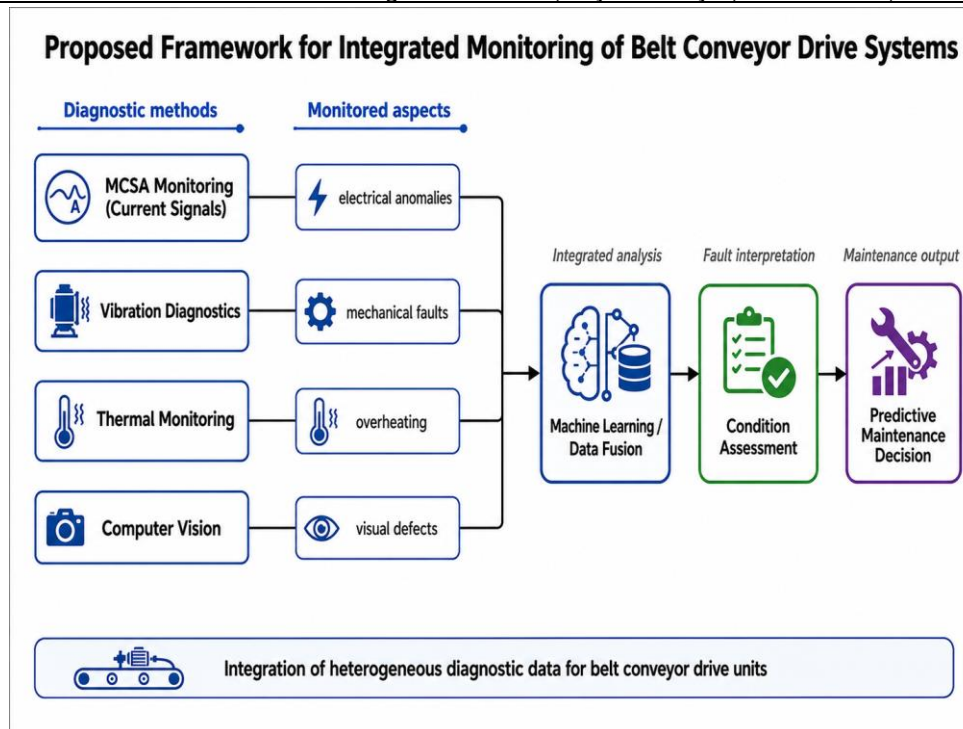


Fig. 3. Proposed framework for the integration of MCSA, vibration diagnostics, thermal monitoring, and computer vision in predictive maintenance of belt conveyor drive systems

The framework consists of three hierarchical diagnostic levels. The first level is continuous online monitoring based on Motor Current Signature Analysis (MCSA), which provides early detection of electrical and electromechanical anomalies without requiring additional sensors on mechanical components. This level serves as the primary screening stage and enables rapid identification of abnormal operating conditions. The second level incorporates vibration diagnostics and thermal imaging monitoring. Vibration analysis is used for detailed assessment of bearings, gearboxes, couplings, and rotating assemblies, while thermal imaging provides information on localized overheating, friction processes, lubrication degradation, and abnormal load distribution. The combined application of these methods significantly improves diagnostic reliability and reduces false-positive indications. The third level includes computer vision technologies and machine-learning-based decision support systems. Visual inspection algorithms are employed to detect belt damage, misalignment, surface defects, and structural abnormalities. Machine learning models integrate information obtained from electrical, vibration, thermal, and visual sources to predict defect progression and estimate the remaining useful life of critical conveyor components. According to the proposed framework, diagnostic information is processed sequentially from data acquisition and anomaly detection to defect classification, condition assessment, and maintenance decision-making. Such integration enables the transition from periodic maintenance to predictive maintenance strategies and improves the operational reliability and safety of belt conveyor systems. The proposed framework may serve as a methodological basis for the development of intelligent monitoring systems capable of combining heterogeneous diagnostic data within a unified industrial condition monitoring platform. Previous investigations have also demonstrated that optimization of conveyor drive-support structures contributes to improved operational reliability and reduced mechanical loading (Bortnovski et al., 2022). Dynamic modelling of

belt-drive systems further improves understanding of transient operating conditions and supports the development of more effective predictive maintenance strategies (Hazai et al., 2020)

LIMITATIONS OF THE REVIEW

This review has several limitations. The analysis was restricted to publications indexed in the selected scientific databases and published in English or Russian between 2017 and 2025. Some industrial diagnostic solutions implemented at mining enterprises remain unavailable in open scientific literature and therefore could not be included. In addition, direct quantitative comparison between studies was limited because different authors used different datasets, experimental conditions, evaluation metrics, and equipment configurations. Consequently, the presented comparison should be considered a qualitative assessment of current technological trends rather than an absolute ranking of diagnostic methods.

CONCLUSION

The conducted review of scientific publications demonstrated that modern monitoring of belt conveyor drive systems is primarily based on the application of non-destructive testing methods, including vibration diagnostics, thermal imaging inspection, Motor Current Signature Analysis (MCSA), computer vision technologies, and intelligent diagnostic systems. The analysis of the reviewed studies showed that vibration diagnostics and MCSA methods provide the highest sensitivity to early-stage defects, while thermal imaging and visual inspection methods are effective for identifying localized damage and abnormal operating conditions. Recent studies also confirm the growing role of machine learning and computer vision algorithms in automating defect detection and condition assessment. The literature analysis revealed that none of the considered diagnostic methods is capable of providing a complete assessment of the technical condition of belt conveyor drive systems when used independently. Most reported approaches focus on specific equipment components or individual defect categories. Furthermore, industrial validation of integrated monitoring systems remains limited, and many published studies are still based on laboratory-scale investigations. Based on the findings of this review, the authors recommend the development of integrated predictive maintenance systems combining electrical, vibration, thermal, and visual diagnostic methods within a unified monitoring platform. A key scientific contribution of this work is the proposed framework that systematizes the interaction between MCSA, vibration diagnostics, thermal monitoring, computer vision, machine-learning-based data fusion, condition assessment, and predictive maintenance decision-making. This framework is not limited to a descriptive classification of diagnostic methods but provides an integrated methodological structure for designing intelligent monitoring systems for belt conveyor drive units. Such systems would enable more reliable condition assessment, improved fault detection accuracy, and enhanced decision-making for maintenance planning. Future research should focus on the development of industrial-scale multimodal monitoring systems integrating electrical, vibration, thermal, acoustic, and visual diagnostic data within unified digital platforms. Particular attention should be devoted to data fusion algorithms, explainable artificial intelligence, digital twin technologies, edge-computing solutions, remaining useful life prediction models, and autonomous maintenance decision-support systems. The creation of publicly available industrial datasets and standardized validation procedures is also

essential for improving the comparability and reliability of future studies. The proposed framework for integrating heterogeneous diagnostic data may serve as a basis for the development of next-generation intelligent monitoring systems aimed at improving the reliability, safety, and operational efficiency of belt conveyor installations. Thus, the proposed framework represents the authors' original contribution to the field of conveyor condition monitoring and can be used as a foundation for future intelligent predictive maintenance systems based on heterogeneous diagnostic data. The proposed framework shown in Fig. 3 demonstrates the integration of MCSA, vibration diagnostics, thermal monitoring, and computer vision into a unified predictive maintenance architecture, thereby emphasizing the scientific contribution of this review.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest regarding this study, whether financial, personal, authorship-related, or otherwise, that could have influenced the research and its results presented in this article.

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DATA AVAILABILITY

The manuscript has no associated data.

USE OF ARTIFICIAL INTELLIGENCE

The authors confirm that they did not use artificial intelligence technologies in the preparation of this work.

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