A Review of Fault Detecting Devices for Belt Conveyor Idlers

Fahad Alharbi[1,2*], Suhuai Luo[1]

[1]*School of Information and Physical Sciences, The University of Newcastle, Newcastle, NSW 2308, Australia*
[2]*Department of Information Technology, College of Computers and Information Technology, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia*
Corresponding author: fahad.alharbi10@uon.edu.au

Article history:
Received: 25 December 2023 / Received in revised form: 11 February 2024 / Accepted: 27 February 2024
Available online 13 March 2024

ABSTRACT

The shift towards automated inspection methods represents considerable progress in conveyor system maintenance, enhancing safety and efficiency while posing challenges in data analysis and implementation costs. This study critically analyses sensor technologies and inspection methods for detecting faults in conveyor belt idlers, highlighting their essential role in preserving the operational integrity of industrial conveyor systems. By synthesizing various research findings, the study assesses the effectiveness of different sensor devices in identifying defects, including built-in sensors, fixed sensor options like acoustic, ultrasonic sensors, cameras, accelerometers, and Distributed Optical Fibre Sensors (DOFS), as well as mobile sensor systems. Our findings emphasize the accuracy of robot-based systems in identifying bearing defects, the comprehensive coverage provided by drones for medium-scale inspections, the constant monitoring offered by integrated idler sensors, and the ability of fixed sensors to detect mechanical faults despite environmental challenges. This research adds to the ongoing discussion on enhancing conveyor system dependability through technological advancements, providing insights into potential future developments that could further refine maintenance strategies in the sector.

Keywords: *Conveyor idler inspection, fault detection and diagnosis, inspection devices, sensor devices, sensor technologies*

I. Introduction

In the mining industry, belt conveyor systems are widely used to transport bulk materials [1],[2]. They have proven highly efficient and reliable for long-distance transportation of mining materials with relatively low operating costs. These systems contribute significantly to the economic development and sustainability of countries worldwide. Several countries, such as Australia and the United Kingdom, have increased their investment in belt conveyor systems. Approximately 40% of Australia's exports come from the mining industry, which requires belt conveyor systems [3]. These systems consist of key components such as the drive unit, pulleys, conveyor belts, and idler rollers. Idlers, in particular, play a vital role in supporting the conveyor belt across its entire stretch and they are distributed extensively, making them challenging to monitor [4]. Due to their significant role and the difficulty in monitoring, idlers are prone to failures, contributing to more than half of all conveyor system breakdowns [5]. When components like idlers fail, it can lead to substantial disruptions in the production process, resulting in downtime, financial losses, and safety hazards [6]. Therefore, ensuring the safety and functionality of the belt

DOI:10.17977/um016v8i12024p039

conveyor infrastructure necessitates regular inspections and preventive maintenance of the belt conveyor idlers.

The development of belt conveyor systems traces its origins back to the late 1800s [7]. No matter their age, size, or complexity, these conveyors operating under the tough conditions commonly found in mining sites require consistent inspection and maintenance. Traditionally, inspections involved manual checks, where inspectors would walk the length of the conveyor, listening for any irregularities that might indicate malfunctions. With advances in technology, the introduction of mechanical sensors marked a significant shift in how conveyor idlers' conditions are monitored, enabling the detection of issues like misalignment, internal problems, and overheating. Enhancing the reliability of these systems necessitates focusing on the individual components, particularly idlers, which are crucial for their smooth operation. Over the years, a variety of inspection methods have been implemented to monitor the health of belt conveyor idlers [8]. These methods have increasingly incorporated Fault Detection and Diagnosis (FDD) sensors and devices, often employing machine learning (ML) models to enhance accuracy and efficiency [9]. The integration of FDD in conveyor systems represents a significant step from traditional manual inspections, offering real-time monitoring and early detection of potential issues, thereby reducing downtime and maintenance costs.

This paper addresses the crucial challenge of maintaining operational integrity and reducing downtime in belt conveyor systems used in the mining industry, focusing particularly on the essential role of idler components. Despite the high efficiency and reliability of these systems in moving bulk materials, idler failures can lead to significant issues, such as production stops, financial losses, and safety hazards. The study critically examines the development and efficacy of various sensor technologies and inspection tools in detecting and preventing idler failures. By analyzing these methods, this paper aims to provide insights into optimal maintenance and monitoring practices for idlers, thereby improving overall system reliability and safety.

1. Contribution of the Paper

To our knowledge, there is a lack of comprehensive reviews that systematically compare and classify sensors and devices for fault detection in belt conveyor idlers. Liu et al. [10] explored various belt damages and their prevention methods but lacked details on specific inspection devices or sensors. Alharbi et al. [9] focused on ML models for fault detection using acoustic and vibration signals, highlighting ML's importance in predictive maintenance but did not elaborate on the actual inspection technologies. Our study aims to bridge this gap by thoroughly investigating and evaluating existing literature on various inspection techniques and sensor technologies in this field. Morales el al. [8] reviewed idler condition monitoring systems for critical overland conveyors, emphasizing the need for wireless, smart, and self-powered systems in transitioning to predictive maintenance. By offering an updated analysis of the latest devices and sensors for idler condition monitoring, our review not only synthesizes the current state of knowledge but also sets the stage for future advancements in data acquisition and analysis crucial for Fault Detection and Diagnosis (FDD), marking a pivotal contribution towards improving conveyor system reliability and maintenance strategies.

2. Information Sources and Search Strategy

This review, covering literature up to November 2023, was conducted using Google Scholar, chosen for its extensive access to key peer-reviewed journals and conference proceedings on belt conveyor idlers. The research involved cross-referencing, forward-searching citations, and sourcing papers from lesser-known libraries.

A systematic bibliographic search used specific terms related to three main concepts: (1) "belt conveyor idlers," using terms like "belt conveyor," "conveyor belt," "idler," and "roller," (2) "fault detection," with terms like "Failure," "Fault," "detect," "diagnose," “condition-based maintenance,” “predictive maintenance,” and “prognostics,” and (3) "inspection and sensor devices," involving "inspection," "sensors," and "devices." The search, combining these terms with AND/OR operators resulted in 764 articles. From these, 34 papers were selected for a full-text review, detailed in Table 1, which outlines the inclusion and exclusion criteria.

Table 1. Inclusion and exclusion criteria

Inclusion criteria
1- Only articles specifically focusing on the diagnosis and detection of failures in belt conveyor idlers. 2- Articles that discuss fault detection and diagnosis (FDD) techniques for belt conveyor idlers written exclusively in English.
Exclusion criteria
1- Articles not written in English. 2- Articles that concentrate on FDD in various components of the belt conveyor system other than idlers. 3- Articles that do not incorporate the use of sensors or inspection devices in their methodologies. 4- Articles that fail to specify the types of detection devices or sensors used. 5- Duplicate articles

3. *Organization of the Paper*

Section 2 of the paper provides an overview of the common defects encountered in belt conveyor idlers. Section 3 of the paper delves into various sensors for detecting belt conveyor idler defects, focusing on their ability to identify specific defect types. It includes a comparative analysis of each sensor's strengths and weaknesses in idler defect detection. The following section broadens the scope of inspection devices and vehicles used in examining conveyor idlers. It discusses both single-sensor devices and multi-sensor systems, offering an overview of current technological progress in this area. This section also categorizes these tools and summarizes their capabilities and limitations. In Section 4, the paper integrates findings from earlier sections and concludes with a summary highlighting key insights, suggesting future research directions and potential advancements in conveyor idler inspection.

II. Types of Defects for Belt Conveyor Idlers

This section explores the various defects that belt conveyor idlers might experience, vital for the continuous and reliable operation of conveyor systems. Belt conveyor idlers consist of parts like the shell, shaft, bearings, hoses, and seals, and their failure can significantly disrupt conveyor functionality [9]. Defects typically manifest in the bearings and rollers, which are crucial for idler operation, and can range from incipient to catastrophic [11]. Incipient defects, such as spalling or fatigue from rolling element deterioration, can evolve into final faults like excessive noise or jamming, potentially leading to catastrophic failures that halt the entire system and pose safety hazards, including fire risks. Advanced stages of failure are often accompanied by increased thermal infrared emissions [12], underscoring the importance of early detection through appropriate sensor technologies to prevent severe damage and maintain operational integrity. Figure 1. shows idler rolls in a typical conveyor operation.

Fig. 1. Idler rolls are shown in operation on a typical belt conveyor [9].

The bearings play a pivotal role in the roller's performance, essential for the smooth functioning of the idler rolls [4], [13]. Bearing faults are especially harmful as they directly affect the idler's smooth rotation. Such faults typically stem from normal wear and tear, insufficient lubrication or contamination, spalling, cracks, or outright bearing failure. For instance, Liu et al. [8] conducted a study on idler failures by analyzing acoustic data from bearings with intentional defects, such as damage to the bearing itself, the cage, and the cover, which were identified as critical factors leading to severe and ultimate failures in conveyor systems. Similarly, roller defects can be caused by surface damage, misalignment, or debris accumulation, affecting the roller's motion and the belt's alignment. Research by Peng et al. [14] and others [15],[16] has categorized roller failures and developed binary fault detection techniques to distinguish between normal and defective conditions through sound and vibration analysis.

Identifying these faults heavily relies on analysing the acoustic and vibrational signatures produced by the idlers. Healthy idlers typically operate quietly, especially in the mid to high-frequency ranges. Bearing faults introduce specific disturbances in these frequencies, marked by periodic impacts or friction, identifiable through advanced signal analysis. While roller faults may not produce distinct acoustic signals, they alter vibration patterns or operational sounds, detectable through sophisticated sensors designed for acoustic, vibration, and thermal monitoring. This early detection is key to timely maintenance and ensuring the conveyor system's longevity and safety.

III. Sensors for Detecting Belt Conveyor Idlers Defects

Sensors for detecting defects in belt conveyor idlers can be broadly classified into three categories: idlers with integrated sensors, fixed sensors, and mobile sensor systems [17], as illustrated in Figure 2. The first category involves the use of 'smart idlers', where sensors are integrated directly into the idlers. These sensors, either singular or combined, are embedded within the roller to identify abnormal temperature increases. The second category encompasses fixed sensors mounted within the belt conveyor idler's frame. This group includes various sensors, such as acoustic, ultrasonic, accelerometer, thermal sensors, and Distributed Optical Fibre Sensing (DOFS). The third category comprises mobile sensor structures. These sensors are either dedicated to a single conveyor system or designed to be detachable and transportable, allowing for flexible use across different conveyors. The following sections will delve deeper into these sensor categories, elaborating on their distinct operational roles, benefits, and possible limitations.

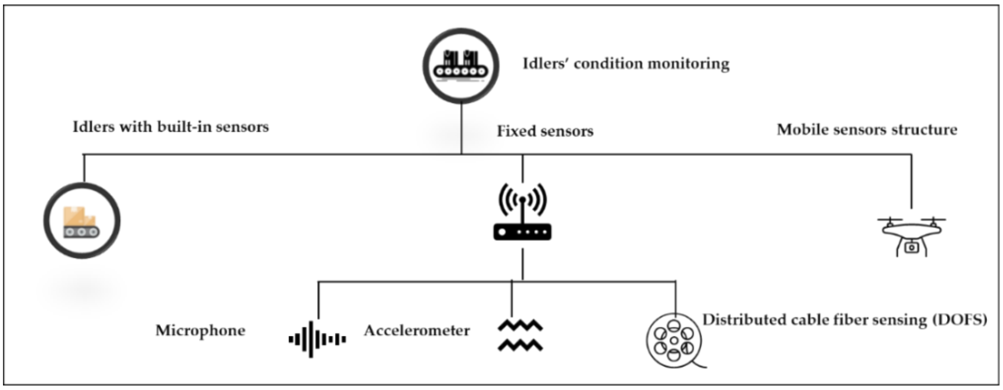

Fig. 2. Sensor types used for idlers inspection [9].

1. Idlers with Built-in Sensors

This sensor type, integrated into idler rolls, remotely measures temperature and vibration. These sensors, functioning as Internet of Things (IoT) devices, have been explored for their ability to capture data. Studies have proposed their use [18], [19], and research into Radio Frequency Identification (RFID) systems for conveyor monitoring has also been conducted [20],[21]. RFID-equipped rollers can be remotely identified, facilitating monitoring [22].

Such idlers, termed 'smart idlers', include sensors, data communication, and intelligent algorithms, allowing for autonomous decision-making [23]. Lodewijks et al. [24] studied IoT applications for conveyors, including smart idlers with RFID tags. Companies like Ingenuity [25] and Vayeron Pty Ltd [26] offer similar technologies. However, smart idlers are most effective in clustered conveyor parts, like near the head pulley [24]. Their widespread use along the belt is limited by the need to replace all existing rollers with smart models, a resource-intensive task due to the large number of rollers. Figure 3 illustrates sensor types and their associated faults.

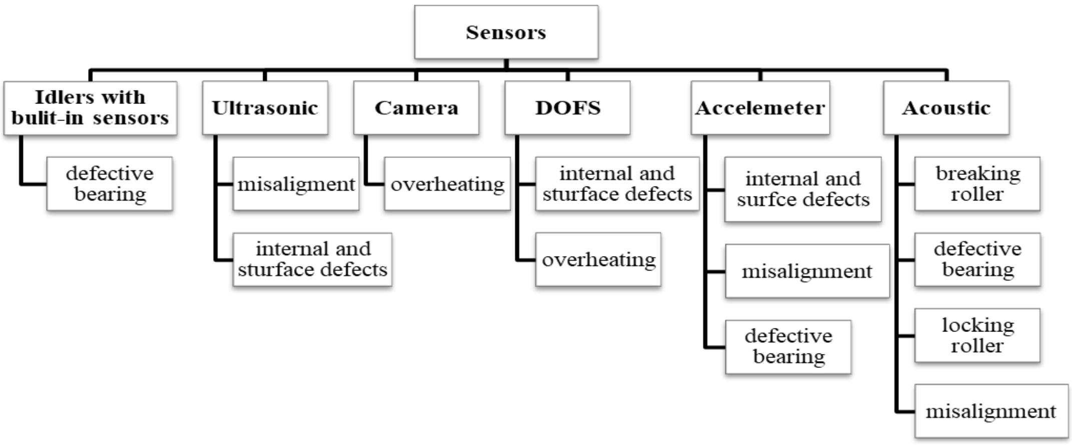

Fig. 3. Sensors and faults related to them

2. Fixed Sensors

This section addresses non-destructive testing (NDT) sensors, which are either directly or indirectly mounted on the frames of idlers. NDT sensors are crucial in inspecting equipment without inflicting damage, thus facilitating ongoing maintenance and operational efficiency. The array of NDT sensors includes acoustic sensors or microphones, ultrasonic sensors, distributed fibre optic sensors (DFOS), accelerometer sensors, and thermal sensors or cameras.

i. Acoustic Sensors

Acoustic sensors represent a passive form of non-destructive evaluation. They do not generate an interrogation signal but can detect sound emissions resulting from defects [27]. Microphones, a specific type of acoustic sensor, identify defects in belt conveyor idlers by capturing the vibrations they emit. Acoustic sensors vary in sensitivity, frequency bandwidth, and other dynamic properties. For instance, a setup of six acoustic sensors on a conveyor system can pinpoint roller faults accurately [15]. Liu et al. employed a microphone placed 150 mm away from a roll shaft end to detect defects in idler bearings artificially [28], whereas other research positioned microphones at distances of 30 cm [29] and 20 cm [30] from the bearings to discern failure patterns in separate studies. Zhang et al. [31] developed a machine learning-based fault detection technique utilizing a microphone, a sound acquisition card, and an acquisition program. The outcomes of employing a microphone demonstrated its capability to reliably assess the condition of belt conveyor idlers for faults despite the noise.

Ultrasonic sensors measure distances using sound waves [32], a technique also applicable to belt conveyor idlers. For example, Ericeira et al.[33], The recording was made by positioning the ultrasonic sensor close to the idler bearings to capture defects. However, a significant drawback of these sensors is their vulnerability to disruptions in sound waves, and environmental fluctuations like changes in temperature and humidity can significantly affect their performance.

ii. Distributed Optical Fibre Sensors (DOFS)

Distributed Optical Fibre Sensors (DOFS) use optical fibre as sensors to measure temperature, strain, and acoustic signals, offering a streamlined alternative to multiple sensing elements for real-time monitoring [34]. These sensors detect external disturbances through the backscattering of light, where light emitted from a source is scattered back upon encountering an event along the fibre. This technology was proven effective in identifying idler damage on a test rig mimicking cable belt conveyors [35].

Field tests of DOFS, including a ten-month study in Western Australia, have successfully detected bearing faults, thermal faults, and shell collapses [36]. Researchers like Hicke et al. [37] and Hoff [38] have demonstrated DOFS's ability to distinguish between healthy and damaged idlers by measuring vibration and temperature variations, which is crucial for early fault detection and fire hazard prevention. Yang conducted tests confirming the suitability of this technology for assessing roller conditions [39]. However, implementing this technology requires careful analysis to position optical cables optimally and mitigate environmental factors like humidity and dust.

iii. Accelerometer Sensors

Accelerometer sensors are integral in the inspection of belt conveyor idlers. These electromechanical sensors are adept at measuring vertical and horizontal acceleration signals, crucial mechanical variables resulting from vibrational forces [27]. In the context of belt conveyor idlers, such vibrations often indicate underlying issues such as defective or worn bearings or broken rollers. For example, Li et al. [6] suggested the installation of a single accelerometer to monitor vibrations from multiple idlers. Numerous laboratory studies [40-44] have employed accelerometer sensors to examine self-aligning conveyor rollers (SACR), a key component in coal belt conveyors. Bortnowski et al. [45] developed a novel approach involving a wireless measuring device that traverses the conveyor belt to record transverse vibration signals via accelerometer sensors. This technique is particularly effective in detecting surface damage on roller tubes, imbalances in rollers, and radial run-outs caused by either substandard roller quality or bearing degradation.

Roos and Heyns [46] and Kaur et al. [47] also successfully used accelerometers for fault detection in idler bearings. However, implementing accelerometer sensors for fault detection in idlers presents certain challenges. The primary issue lies in the sheer number of idlers within a conveyor system, which necessitates an impractically large number of accelerometers, leading to prohibitive costs. This limitation underscores the need for more cost-effective and efficient methods for detecting faults in conveyor idler systems.

iv. Cameras

High-resolution and thermographic cameras are increasingly used to inspect idlers on belt conveyors. These cameras enable automatic visual inspection systems to detect idlers defects using advanced image processing. Thermographic cameras, which use thermal imaging based on infrared technology, non-invasively record temperature variations on idler surfaces, often indicating defects.

Frameworks for semi-autonomous inspections using thermal cameras have been suggested by Nascimento et al. [2] and Carvalho et al. [17], while Angelo et al. [48] developed an automated image capture method to identify roller faults. However, temperature-based fault detection can be time-consuming, potentially limiting these systems' practicality in fast-paced industrial settings where quick detection is essential.

3. Mobile Structure Sensors

This category of sensors encompasses robots and Unmanned Aerial Vehicles (UAVs) that are equipped with the various types of sensors described in the fixed sensors section. These sensors can be specifically tailored for a single belt conveyor system or designed as detachable, independent, transportable units across different systems. One notable example, as referenced in [49], involves a robot engineered to navigate along the conveyor frame, capturing infrared thermal images to assess the temperature of the rollers. However, a significant limitation of this approach is the impracticality of mandatory adaptations to the conveyor system.

On the other hand, UAV-based sensor systems offer greater flexibility and potential for cost savings. Such systems can simultaneously monitor multiple belt conveyor idlers, making them a more versatile choice. An innovative application of this concept is demonstrated in an article [17], where a UAV equipped with a thermal imaging camera represents a new method for roller inspection. Early findings suggest that these UAVs can automatically detect roller failures through advanced signal processing techniques. Compared to the expenses associated with installing and maintaining fixed sensors for each idler and an entire inspection system, the use of mobile sensor structures like UAVs presents significant advantages, especially in the mining industry. Their ability to concurrently inspect numerous idlers makes them a highly efficient and cost-effective solution. Table 2. Provide a summary and comparison of sensors applied in belt conveyor idlers inspection.

Table 2. Summary and comparison of sensors applied in belt conveyor idlers inspection.

Method	Types of faults	Advantages	Major drawbacks	Studies
Idlers with built-in sensor	Bearing failure, temperature	Real-time data and early fault detection.	High costs due to embedded sensors in each idler and complex installation across distributed infrastructures.	[18], [20], [21], [24]
Acoustic sensor	Broken roller, roller off-centre rotation, stuck or fractured roller, bearing outer ring fault	Detects a range of mechanical faults through sound, even in the early stages.	Challenges in pinpointing sound sources due to ambient noise and interference.	[14], [15], [50]
Microphone	Wear, corrosive wear, manufacturing errors, stuck or blocked bearings	Sensitive to sound, indicating wear or damage.	Difficulty isolating conveyor noises from environmental sounds.	[12], [28], [29], [31], [51], [52]
Ultrasonic	Abnormal vibration, eccentric rotation, noise emission, sealing issues, oxidation, elongated roll extremities	Effective for internal defect detection and distance measurements	Susceptible to disturbances in sound waves.	[33]
DOFS	Bearing faults, thermal faults, shell collapses, damaged idler bearings, polyurethane tyre wear	Comprehensive, continuous monitoring along the conveyor.	Requires precise optical cable positioning and isolation of environmental factors.	[35-39]
Accelerometer	Surface defects of roller tubes, roller unbalance, radial offset, defective bearings and shafts	Accurate in detecting imbalances and misalignments.	Installation challenges and ineffective vibration transmission.	[6], [40-47]
Camera	Idler bearing failures, roller blocking, side roller, centre-right roller, centre-left roller, abnormal temperature rise	Detects surface-level defects and abnormalities.	Lens blockage and image clarity issues industy environments.	[2], [12], [17],[29], [48],[49], [53]

4. Inspection Devices

The belt conveyor idler inspection devices are designed to detect a wide range of belt conveyor defects. The capabilities of these devices can vary according to the sensors installed on them. The devices can be divided into two main categories: robots and drones. This section examines various examples of how these devices are being used to inspect and detect faults for belt conveyor idlers.

1. Robots

Inspection robots, equipped with advanced vision sensors, are increasingly used for inspecting high-value belt conveyor idler infrastructure. They vary in autonomy, from semi-autonomous robots following set paths to fully autonomous ones navigating independently. Research has explored robotic vehicles for idler inspection [52], [54-57], both above and below conveyors. Szrek et al. [53] introduced a semi-automated, wheeled robot prototype, while another study [58] used Unmanned Ground Vehicle (UGV)-based robots with RGB and IR cameras for detecting overheated idlers.

Innovations include a wheel-and-track system for continuous data collection using acoustics, thermography, and laser scanners for precise mapping [29]. Another approach features a mobile platform suspended between conveyor belts for infrared thermography inspections [49]. A legged robot using an acoustic approach with integrated cameras, microphones, and accelerometers has also been proposed [51]. However, each robot type has drawbacks: wheel-and-track robots may be slow and inefficient due to frictional issues, while legged robots can be complex and challenging to control, especially in demanding environments like mines.

2. Drones

Drones, or Unmanned Aerial Vehicles (UAVs), are mobile robots capable of autonomous or remote-controlled flight, effectively identifying idler defects like abnormal temperature changes. They navigate preprogrammed paths using advanced systems, offering rapid and easy information gathering for belt conveyor idler inspections. Drones expedite inspections, reducing inspectors' need for physical access, especially in hazardous or hard-to-reach areas.

Capable of speeds up to 30 km/h, drones can be equipped with various sensors, including thermographic and high-definition cameras. For instance, a study [17] demonstrated their effectiveness in semi-automated thermographic inspections in mining. However, drones have limitations, such as financial risks from crashes and reduced efficacy in adverse weather, limiting their use to specific conditions. A summary and comparison of inspection devices for belt conveyor idlers are provided in Table 3.

Table 3. Summary and comparison of inspection devices applied in belt conveyor idlers inspection

Method	Sensor	Types of faults	Preferred inspection coverage	Advantages	Major drawbacks	Studies
Robots	Camera, microphone, accelerometer, and other complementary sensors to move the robot	Defective bearing	Suitable for small to medium-scale inspections.	High precision in fault detection, ability to navigate and inspect in complex environments, and versatility in sensor integration for comprehensive assessments.	Challenges include navigating barriers, stairs, and general mobility issues.	[29], [49], [51-58]
Drones	Camera	Overheating	Appropriate for medium-scale inspections.	Quick, extensive area coverage, ideal for hard-to-reach or dangerous locations, and high-resolution imaging for detailed inspections. Reduced need for human presence in risky areas.	Drones have limited flight time (up to 1 hour), payload capacity (up to 10 kg for top models), and face operational challenges in indoor areas, bad weather, and windy conditions. Regulatory restrictions can also limit autonomous flights.	[2], [17]

IV. Discussion

Exploring sensor technologies and methodologies for inspecting conveyor belt idler rollers has been extensive and diverse. This discussion synthesizes key findings from various studies, offering insights and interpretations that address the research problem and providing implications and recommendations for inspecting conveyor idler faults using different tools and sensors.

1. Synthesis of Findings

- **Robot-Based Systems:** These systems, incorporating cameras, microphones, and accelerometers, demonstrate high precision in detecting bearing defects, particularly effective in small to medium-scale inspections. Their main limitation lies in their mobility, particularly in navigating complex environments.
- **Drone Technology:** Equipped with cameras, drones excel in medium-scale inspections, particularly for overheating issues. Their strengths lie in rapid, extensive area coverage and high-resolution imaging, which are valuable in difficult-to-access or hazardous locations. However, constraints such as limited flight time, operational difficulties in adverse weather, and regulatory restrictions curtail their full potential. The limited battery autonomy of UAVs raises another important question. Sensor structures on the vehicles and data transmission contribute significantly to the problem. As discussed in Suzuki et al. [59] and Toksoz et al. [60], such limitations may be mitigated through the use of battery replacements and recharge stations.
- **Idlers with Integrated Sensors:** These systems offer direct, continuous monitoring from the idler, facilitating real-time fault detection. The major hindrance is the cost associated with embedding electronic sensors in each idler and the complexity of their installation over extensive areas.
- **Acoustic Sensors and Microphones:** These sensors can detect various mechanical faults through sound analysis. However, ambient noise and interference can make pinpointing the exact sources of sounds challenging.
- **Ultrasonic Sensors:** These sensors are effective for internal defect detection and distance measurements, though their performance is susceptible to disturbances in sound waves.
- **Distributed Optical Fibre Sensors (DOFS):** DOFS stands out for providing continuous, distributed monitoring along the conveyor. Nevertheless, they face operational challenges, including the need for precise optical cable positioning and environmental factor isolation.
- **Accelerometers** are precise in measuring vibrations and can detect imbalances and misalignments in conveyor systems. Installation difficulties and the ineffective transmission of vibrations are their primary drawbacks. To address these issues, research such as that conducted by Li et al. [6] and Bortnowski et al. [45] have explored innovative solutions. One approach involves attaching a single acceleration sensor to gather vibration data from multiple idlers, thereby minimizing the need for numerous sensors. Another strategy employs a mobile wireless device that travels along the conveyor, capturing the transverse vibration signals and offering a more dynamic and less intrusive monitoring method.
- **Cameras:** Cameras, though capable of visual inspection capabilities, often struggle to identify early-stage faults in conveyor systems [9]. Adverse weather conditions can compromise their effectiveness by obscuring the lens and diminishing image clarity.

Consequently, this limitation tends to delay fault detection until issues have evolved into more pronounced and advanced stages.

2. *Implications of Technological Advancements*

The transition from manual inspection methods to advanced sensor-based technologies in conveyor systems underscores a movement towards increased automation and safety. This evolution is marked by the integration of drone and robotic technologies, addressing the inefficiencies of fixed sensor systems. Despite offering enhanced precision and broader coverage, these sophisticated systems introduce new challenges, such as operational limitations and higher implementation costs.

3. *Recommendations for Future Implementations*

In addressing conveyor idler faults, a strategic combination of sensor types may yield optimal results:

- **For Extensive Systems:** Drone technology is recommended for its wide coverage, particularly in challenging areas. Zimroz et al. [61] validated the use of drones for recording the acoustic signals of idlers, contrasting it with conventional vibration detection methods. Utilizing time-frequency analysis and short-time Fourier transforms (STFT), the study efficiently minimized noise through high-pass filtering, illustrating that drones equipped with microphones can precisely identify faults in rotating equipment. This underscores the potential of drones for effective surveillance of conveyor systems in areas that are difficult to access, indicating a future trend towards integrating drone technology with sophisticated signal analysis for enhanced industrial maintenance.
- **For In-Depth Analysis:** Robot-based systems or idlers with built-in sensors are more suitable for detailed, localized inspections.
- **Cost-Efficiency and Coverage Balance:** A blend of acoustic sensors, DOFS, and accelerometers can provide a cost-effective solution with reasonable accuracy and coverage.

The selection of appropriate inspection tools should be tailored to the conveyor system's scale, the specific types of faults anticipated, and the prevailing environmental conditions. The focus of innovation should be two-pronged: embracing futuristic technologies while also enhancing the efficiency, safety, and reliability of current systems. This balanced approach ensures that conveyor systems not only adapt to emerging technologies but also remain effective in addressing present-day operational challenges, thus fostering a pragmatic evolution in conveyor system designs.

V. Conclusions

This study has investigated a range of sensors and inspection devices, assessing their suitability for detecting defects in belt conveyor idlers. The choice of the appropriate inspection tool depends on the specific faults to be detected, as each tool has unique strengths and limitations. The findings of various studies underscore that adopting drones or robots significantly enhances the inspection process. These advanced technologies not only make inspections more realistic and accessible but also improve efficiency and precision. Consequently, investing in these modern inspection methods is a strategic move towards optimizing maintenance practices in the mineral industry, ensuring the continued reliability and efficiency of belt conveyor systems. Future research should consider developing hybrid inspection systems that merge different sensor technologies' strengths to address their shortcomings. There is also significant potential in applying artificial intelligence and machine learning to analyze the extensive data from these tools, aiming for more accurate and proactive failure predictions. Investigating these advanced technologies' long-term economic and operational benefits in real-world settings will further illuminate their practicality and advantages, guiding the mining industry toward more effective maintenance practices.

References

[1] M. Alspaugh, *Latest developments in belt conveyor technology.* MINExpo 2004, September 2004.

[2] R. Nascimento, R. Carvalho, S. Delabrida, A. Bianchi, G. Uzeda, G. Luis, and R. Rabelo, "An integrated inspection system for belt conveyor rollers - advancing in an enterprise architecture", *19th International Conference on Enterprise Information Systems*, April 2017, doi: 10.5220/0006369101900200

[3] G. Barfoot, *Advances in the non-destructive testing of conveyor belting*, The University of Newcastle, Australia, 2007.

[4] A. Reicks, *Belt conveyor idler roll behaviors.* Bulk Material Handling by Conveyor Belt 7, 2008: pp. 35-40.

[5] R. Zimroz and R. Król, *Failure analysis of belt conveyor systems.* Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej, 2009, pp. 50-51.

[6] W. Li, Z.Wang, Z. Zhu, G. Zhou, and G. Chen, "Design of online monitoring and fault diagnosis system for belt conveyors based on wavelet packet decomposition and support vector machine", *Advances in Mechanical Engineering*, January 2013, vol. 5, p. 797183, doi: 10.1155/2013/797183

[7] Harrison, "A. Influence of Australian research on conveyor technology", in *13th International Conference on Bulk Materials Storage, Handling and Transportation (ICBMH 2019)*. 2019. Engineers Australia Barton, ACT.

[8] A.S. Morales, P. Aqueveque, J.A. Henriquez, F. Saavedra, and E.P. Wiechmann, "A technology review of idler condition based monitoring systems for critical overland conveyors in open-pit mining applications", *IEEE Industry Applications Society Annual Meeting*, Cincinnati, OH, USA, 2017, pp. 1-8, doi: 10.1109/IAS.2017.8101839.

[9] F. Alharbi, S. Luo, H. Zhang, K. Shaukat, G. Yang, C.A. Wheeler, and Z. Chen, "A brief review of acoustic and vibration signal-based fault detection for belt conveyor idlers using machine learning models", *Sensors*, vol. 23, no. 4, pp. 1902, 2023, doi: 10.3390/s23041902

[10] P. Bortnowski, W. Kawalec, R. Król, and M. Ozdoba, "Types and causes of damage to the conveyor belt – Review, classification and mutual relations", *Engineering Failure Analysis*, vol. 140, p. 106520, 2022, doi: 10.1016/j.engfailanal.2022.106520.

[11] X. Liu, Y. Pang, G. Lodewijks, and D. He, "Experimental research on condition monitoring of belt conveyor idlers", *Measurement*, vol. 127, pp. 277-282, 2018, doi: https://doi.org/10.1016/j.measurement.2018.04.066.

[12] Y. Liu, C. Miao, X. Li, J. Ji, and D. Meng, "Research on the fault analysis method of belt conveyor idlers based on sound and thermal infrared image features", *Measurement*, vol. 186, p.1101772021, doi: 10.1016/j.measurement.2021.110177.

[13] M. Vasić, B. Stojanović, and M. Blagojević, "Failure analysis of idler roller bearings in belt conveyors", *Engineering Failure Analysis*, vol. 117, p. 104898, 2020.

[14] C. Peng, Z. Li, M. Yang, M. Fei, and Y. Wang, "An audio-based intelligent fault diagnosis method for belt conveyor rollers in sand carrier", *Control Engineering Practice*, vol. 105, p. 104650, 2020, doi: 10.1016/j.conengprac.2020.104650.
[15] M. Yang, W. Zhou, and T. Song, "Audio-based fault diagnosis for belt conveyor rollers. *Neurocomputing",* vol. 397, pp. 447-456, 2020.
[16] X.-P. Jiang, and G. Cao, "Belt conveyor roller fault audio detection based on the wavelet neural network", *11th International Conference on Natural Computation* (ICNC), 2015, p. 954-958.
[17] R. Carvalho, R. Nascimento, T. D'Angelo et al., "A UAV-Based Framework for Semi-Automated Thermographic Inspection of Belt Conveyors in the Mining Industry", *Sensors*, vol. 20, no. 8, p. 2243, 2020.
[18] D. Cooper, *Sensor platform for monitoring conveyor belt rollers*, Thesis, University of Southern Queensland, October, 2015.
[19] R. L. de Moura, D. Bibancos, L. P. Barreto, A. C. Fracaroli, and E. Martinelli, "Study Case in Mining Industry: Monitoring Rollers using Embedded LoRaWan", *IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Glasgow, 2021, pp. 1-5, doi: 10.1109/I2MTC50364.2021.9459901.
[20] G. Lodewijks, M.B. Duinkerken, A.M. Cruz, and H.P. Veeke, *The application of RFID technology in belt conveyor systems*, 2014.
[21] Y. Pang, and G. Lodewijks, "The application of RFID technology in large-scale dry bulk material transport system monitoring", *IEEE Workshop on Environmental Energy and Structural Monitoring Systems*, 2011, pp. 1-5.
[22] R. Want, "An introduction to RFID technology", *IEEE Pervasive Computing*, vol. 5, no. 1, p. 25-33.
[23] X. Liu, G. Lodewijks, and Y. Pang, *Intelligent maintenance of large-scale belt conveyor idler rolls: state-of-the-art and opportunities.* TU Delft, 2014: p. 1-5.
[24] G. Lodewijks, W. Li, Y. Pang, and X. Jiang, "An Application of the IoT in Belt Conveyor Systems". In: W. Li et al. *Internet and Distributed Computing Systems. IDCS 2016. Lecture Notes in Computer Science,* vol 9864. pp 340–351, doi: 10.1007/978-3-319-45940-0_31.
[25] *Ingenuity*. Accessed Oct.10, 2023, Available from: https://ingenuitydesigngroup.com/project/smart-idler/.
[26] Vayeron. Accessed Oct.10, 2023 Available from: https://vayeron.com/
[27] A. Falamarzi, S. Moridpour, and M. Nazem, "A Review on Existing Sensors and Devices for Inspecting Railway Infrastructure*", Jurnal Kejuruteraan*, vol. 31, no. 1, pp. 1-10, 2019.
[28] X. Liu, D. Pei, G. Lodewijks, Z. Zhao, and J. Mei, "Acoustic signal based fault detection on belt conveyor idlers using machine learning", *Advanced Powder Technology*, vol. 31, no. 7, pp. 2689-2698, 2020, doi: 10.1016/j.apt.2020.04.034.
[29] F. Rocha, G. Garcia, R. Pereira et al, "*ROSI:* A robotic system for harsh outdoor industrial inspection - system design and applications", *Journal of Intelligent & Robotic Systems*, vol. 103, no. 2, p. 30, 2021.
[30] Y. Liu, C. Miao, X. Li, J. Ji, D. Meng, and Y. Wang, "A dynamic self-attention-based fault diagnosis method for belt conveyor idlers", *Machines*, vol. 11, no. 2, p. 216, 2023, doi: 10.3390/machines11020216
[31] Y. Zhang, S. Li, A. Li, G. Zhang, and M. Wu, "Fault diagnosis method of belt conveyor idler based on sound signal", *Journal of Mechanical Science and Technology*, vol. 37, no. 1, pp. 69-79, 2023.

[32] S. Campbell, N. O'Mahony, L. Krpalcova, D. Riordan, J. Walsh, A. Murphy, and C. Ryan, "Sensor technology in autonomous vehicles: A review", in *29th Irish Signals and Systems Conference (ISSC)*, 2018, IEEE.

[33] D.R. Ericeira, F. Rocha, A. G. C. Bianchi, and G. Pessin, "Early Failure Detection of Belt Conveyor Idlers by Means of Ultrasonic Sensing", in *International Joint Conference on Neural Networks (IJCNN)*, 2020.

[34] H. Wijaya, *Application of Distributed Acoustic Sensor for Condition Monitoring of Mining Conveyor*, 2022, Swinburne University of Technology Melbourne, Australia.

[35] H. Wijaya, P. Rajeev, E. Gad, and R. Vivekanamtham, "Distributed optical fibre sensor for condition monitoring of mining conveyor using wavelet transform and artificial neural network", *Structural Control and Health Monitoring*, vol. 28, no. 11, p. e2827, 2021.

[36] H. Wijaya, P. Rajeev, E. Gad, and R. Vivekanamtham, "Automatic fault detection system for mining conveyor using distributed acoustic sensor", *Measurement*, vol. 187, p. 110330, 2022, doi: 10.1016/j.measurement.2021.110330.

[37] K. Hicke, M. -T. Hussels, R. Eisermann, S. Chruscicki, and K. Krebber, "Condition monitoring of industrial infrastructures using distributed fibre optic acoustic sensors", in *25th Optical Fiber Sensors Conference (OFS)*, 2017.

[38] H. Hoff, "Using distributed fibre optic sensors for detecting fires and hot rollers on conveyor belts", in *2nd International Conference for Fibre-optic and Photonic Sensors for Industrial and Safety Applications (OFSIS)*, 2017, IEEE.

[39] B.Y. Yang, *Fibre optic conveyor monitoring system*, MPhil Thesis, School of Mechanical and Mining Engineering, The University of Queensland, 2014.

[40] S. Ravikumar, H. Kanagasabapathy, and V. Muralidharan, "Fault diagnosis of self-aligning troughing rollers in belt conveyor system using k-star algorithm", *Measurement*, vol. 133, pp. 341-349, 2019.

[41] S. Ravikumar, S. Kanagasabapathy, V. Muralidharan, S. R. Srijith, and M. Bimalkumar, "Fault diagnosis of self-aligning troughing rollers in a belt conveyor system using an artificial neural network and naive bayes algorithm", in *Emerging Trends in Engineering, Science and Technology for Society, Energy and Environment*. 2018, CRC Press. pp. 425-432.

[42] S. Ravikumar, H. Kangasabapathy, and V. Muralidharan, "Fault diagnosis of Self Aligning carrying Idler (SAI) in Belt-Conveyor System using Statistical Features and Support Vector Machine". in *International Conference on Computational Intelligence & Advanced Manufacturing Research*, 2014, vol 2.

[43] S. Ravikumar, V. Muralidharan, P. Ramesh, and C. Pandian, "Fault Diagnosis of Self-aligning Conveyor Idler in Coal Handling Belt Conveyor System by Statistical Features Using Random Forest Algorithm", *Advances in Smart Grid Technology. Lecture Notes in Electrical Engineering*, vol 688. Springer, Singapore, pp. 207-219, 2021, doi: 10.1007/978-981-15-7241-8_16

[44] V. Muralidharan, S. Ravikumar, and H. Kangasabapathy, "Condition monitoring of Self aligning carrying idler (SAI) in belt-conveyor system using statistical features and decision tree algorithm", *Measurement*, vol. 58, pp. 274–279, 2014.

[45] Bortnowski, P., Król, R., and Ozdoba, M., "Roller damage detection method based on the measurement of transverse vibrations of the conveyor belt". *Eksploatacja i Niezawodnosc - Maintenance and Reliability*, vol. 24, pp. 510-521, 2022.

[46] W. A. Roos, and P. S. Heyns, "In-belt vibration monitoring of conveyor belt idler bearings by using wavelet package decomposition and artificial intelligence",

International Journal of Mining and Mineral Engineering, vol. 12, no. 1, pp. 48-66, 2021, doi: 10.1504/IJMME.2021.114914

[47] A. Kaur, S. Altaf, and S. Iqbal, "Predictive Framework of Conveyor Idler Bearings Fault Monitoring using Efficient Signal Processing Technique", *Journal of Engineering Science & Technology Review*, vol. 15, no. 4, 2022.

[48] T.D. Angelo, M. Mendes, B. Keller, R. Vitor, R. et al., "Deep Learning-Based Object Detection for Digital Inspection in the Mining Industry". in *18th IEEE International Conference On Machine Learning and Applications (ICMLA)*, 2019.

[49] W. Yang, X. Zhang, and H. Ma, "An inspection robot using infrared thermography for belt conveyor", in *13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, 2016.

[50] X. Zhang, S.Wan, Y. He, X. Wang, and L. Dou, "Teager energy spectral kurtosis of wavelet packet transform and its application in locating the sound source of fault bearing of belt conveyor", *Measurement*, vol. 173, p. 108367, 2021.

[51] A. Skoczylas, P. Stefaniak, S. Anufriiev and B. Jachnik, "Belt Conveyors Rollers Diagnostics Based on Acoustic Signal Collected Using Autonomous Legged Inspection Robot", *Applied Sciences*, vol 11, no. 5, p. 2299, 2021.

[52] H. Shiri, J. Wodecki, B. Ziętek, and R. Zimroz, "Inspection Robotic UGV Platform and the Procedure for an Acoustic Signal-Based Fault Detection in Belt Conveyor Idler", *Energies*, vol. 14, no. 22, p. 7646, 2021.

[53] J. Szrek, J. Wodecki, R. Błażej, and R. Zimroz, "An Inspection Robot for Belt Conveyor Maintenance in Underground Mine—Infrared Thermography for Overheated Idlers Detection", *Applied Sciences*, vol. 10, no. 14, p. 4984, 2020.

[54] H. Staab, E. Botelho, D.T. Lasko, H. Shah, W. Eakins, and U. Richter, "A Robotic Vehicle System for Conveyor Inspection in Mining", in *IEEE International Conference on Mechatronics (ICM)*, 2019.

[55] V.P. Kumawat, N. Divate, S. Bansode, A. Patel, and K. Jagtap, "Design and Prototype of Wireless Robot for Condition Monitoring of Coal Conveyor Roller Bearings", *Proc. of Intern. Conf. on Intelligent Manufacturing and Automation*, 2018.

[56] G. Garcia, F. Rocha, M. Torre, W. Serrantola et al, *ROSI: A Novel Robotic Method for Belt Conveyor Structures Inspection*, Belo Horizonte, Brazil, 2019, pp. 326-331, doi: 10.1109/ICAR46387.2019.8981561.

[57] J. Wodecki, H. Shiri, M. Siami, and R. Zimroz, *"Acoustic-based diagnostics of belt conveyor idlers in real-life mining conditions by mobile inspection robot,"* ISMA2022, Leuven, Belgium, 2022.

[58] P. Dabek, J. Szrek, R. Zimroz, and J. Wodecki, "An Automatic Procedure for Overheated Idler Detection in Belt Conveyors Using Fusion of Infrared and RGB Images Acquired during UGV Robot Inspection", *Energies*, vol.15, no.2, p. 601. 2022.

[59] K.A.O. Suzuki, P. K. Filho, and J.R. Morrison, "Automatic Battery Replacement System for UAVs: Analysis and Design", *Journal of Intelligent & Robotic Systems*, vol. 65, no. 1, pp. 563-586, 2012.

[60] T. Toksoz, B. Michini, J. Redding, M. Michini, J. How, M. Vavrina, and J. Vian, "*Automated Battery Swap and Recharge to Enable Persistent UAV Missions"*. Infotech@Aerospace 2011, March 2011.

[61] P. Zimroz, H. Shiri, and J. Wodecki, "Analysis of the vibro-acoustic data from test rig -comparison of acoustic and vibrational methods". *IOP Conference Series: Earth and Environmental Science*, 2021, vol. 942, no. 1, p. 012017.