Industry 4.0 Approaches for Sustainable Real-Time Monitoring and Predictive Maintenance of Conveyor Systems

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Abstract. Industry 4.0 techniques play a pivotal role in revolutionizing real-time monitoring and predictive maintenance of conveyor systems, which are critical assets in modern industries to achieve sustainability. By synthesizing insights from various studies, the article provides a comprehensive perspective on the challenges, emerging trends, and opportunities within this dynamic field. The convergence of sensor technology, machine vision, data analytics, and IoT empowers conveyor systems to proactively address maintenance needs, minimize disruptions, and optimize performance while also promoting sustainability and minimizing environmental impact. Additionally, the multifaceted challenges associated with implementing predictive maintenance, such as data heterogeneity and model maintenance, are discussed, along with the introduction of advanced methodologies for specific issues like belt tear detection and foreign object identification. This highlights the transformative potential of Industry 4.0 techniques in enhancing conveyor systems' operational efficiency and reliability within the context of sustainability, contributing to a greener and more responsible industrial landscape.

Keywords: Sustainability, Conveyor belts, Industry 4.0, Real Time Monitoring, Predictive Maintenance.

1 Introduction

Environmental responsibility and sustainability are becoming the primary objectives of modern industry. The use of conveyor belt systems is a crucial part of this transition since they are critical to reducing waste and conserving energy. By employing cutting-edge Industry 4.0 technologies, such as advanced sensors and intelligent control systems, these conveyor systems have the capacity to facilitate real-time monitoring and predictive maintenance. In order to improve the sustainability and effectiveness of conveyor systems in the manufacturing sector, this article explores the integration of these strategies, optimizing material flow, and minimizing product losses.

Conveyors serve as indispensable assets in modern industries, efficiently transporting goods and streamlining operations [3]. Their pivotal role in material handling underscores their

ICAMDMS 2024, February 23-24, Coimbatore, India

DOI 10.4108/eai.23-2-2024.2347031

significance across various sectors. However, ensuring their seamless operation and longevity necessitates vigilant monitoring of operational parameters [7]. Parameters such as belt speed, alignment, wear, and other performance indicators form the core of comprehensive conveyor monitoring, guaranteeing both efficiency and user safety [7].

With the advent of Industry 4.0, a transformative era emerges, fusing digital technologies with industrial processes. Gupta et al. emphasize the potent blend of sensor technology, machine vision, data analytics, and the Internet of Things (IoT) within the Industry 4.0 framework. This integration empowers conveyor systems with real-time insights and predictive maintenance capabilities. Consequently, conveyor systems can proactively address maintenance needs, minimizing disruptions and optimizing performance.

The convergence of Industry 4.0 and conveyor systems embodies a dynamic field of research and innovation. Bortnowski et al. and Chammro et al. underscore the multidisciplinary nature of this pursuit. By synthesizing the findings from these studies, this literature review offers a comprehensive view of the real-time monitoring and predictive maintenance landscape within the Industry 4.0 framework. In analyzing these works, the review unveils emerging trends, challenges, and opportunities that underline the pivotal role of Industry 4.0 techniques in the continued advancement of conveyor systems across industries.

2 Needs, Issues & Challenges for Real Time Monitoring and Predictive Maintenance of Conveyor Belt System

In industries involved in bulk material handling and transportation, the reliability of belt conveyor systems is of paramount concern. In this study, the focus is on the integration of Industry 4.0 methodologies for achieving sustainable real-time monitoring and predictive maintenance specifically tailored to coal conveyor belt systems. Coal conveyor belts play a pivotal role in various industrial sectors, notably in mining, power generation, and transportation. These systems facilitate the efficient and continuous movement of bulk materials, primarily coal, across various stages of production and distribution processes. The utilization of coal conveyor belts extends from mining operations, where they transport extracted coal from mines to processing plants, to power plants, where they facilitate the transportation of coal for combustion to generate electricity. Given the criticality of coal in energy production and industrial operations, optimizing the performance and reliability of coal conveyor belts through Industry 4.0 approaches is of paramount importance for enhancing productivity, reducing downtime, and ultimately fostering sustainability in these sectors. These systems comprise various crucial components, including belts, pulleys, drive units, and idler rolls, all integrated into a cohesive architectural structure.

2.1 Issues in Conveyor Belts

The sustained operation of conveyor systems heavily depends on ensuring the reliability of these components. Among them, the conveyor belt itself is particularly vulnerable to wear, mainly due to continuous movement, contact with rotating parts, and the transported materials. Wear manifests in two primary categories: localized damage over short belt sections and linear damage that spans the entire loop length. Mistracking, where the belt veers towards one conveyor edge due to geometry imperfections in the belt's run-on idlers, is a prominent issue.

Elements exposed to abrasion, such as rubber belt covers and edges, are especially susceptible to failures, often caused by the penetration or cutting of the carrying cover. Belts with a steel cord core may exhibit corrosion traces, indicating cover rubber discontinuity and core exposure to corrosive agents. Longitudinal cuts, a particularly damaging form of wear, can render belts inoperable and are challenging to detect in a timely manner.

Furthermore, noise and vibration, while not direct damage indicators, are early warning symptoms of irregularities that may result in belt damage or failure. Bulges on belt surfaces may signify potential adhesion loss between steel cables and the rubber core, undermining belt integrity, and increasing wear. Therefore, major issues those need to be given attention to in a conveyor belt system:

- Wear and tear from continuous movement and material contact.
- Mistracking due to geometry imperfections.
- Abrasion of rubber belt covers and edges.
- Sudden emergence of longitudinal cuts, challenging timely detection.
- Indications of abnormalities through noise and vibration of the system.
- Possible adhesion loss between steel cables and the rubber core, weakening the belt

2.2 Need for Predictive Maintenance and Real Time Monitoring

The growing need to overcome the issues discussed, arise from sudden catastrophic failures and significant downtime associated with breakdowns of the conveyor belt system. Repairs can span from hours to days, with safety measures and complex structures impeding inspection and maintenance. Even replacing a minor component might necessitate partial dismantling due to the protective casings safeguarding moving parts. This in turn not only increases the lead time to manufacture and transport the product but also costs associated with maintenance.

By harnessing Industry 4.0 technologies, predictive maintenance holds the potential to transform conveyor system management from a reactive to a proactive approach. Implementing a proper Real Time Monitoring System on the conveyor system enables early detection of wear by continuously monitoring the components and alerting the operator of abnormalities. Sudden failures can be overcome by implementation of appropriate predictive maintenance strategies that are drawn from the data collected from real time monitoring and ensure maintenance before a catastrophic failure.

Therefore, a predictive maintenance system and real time monitoring is needed for a conveyor belt system to combat unplanned downtime, cut increased maintenance costs, increases the machine life, and most importantly promotes sustainability by efficient use of resources and reducing waste that arise die to failures.

2.3 Challenges in implementing Predictive Maintenance Systems in Industries

The implementation of predictive maintenance (PdM) in conveyor belt systems poses significant challenges due to their intricate and diverse nature. These systems often rely on traditional time-based maintenance strategies due to complexities that hinder the seamless adoption of PdM. Limited research articles have addressed successful PdM implementation for conveyors, resulting in an oversight of critical factors like variable load conditions and erratic noise.

Overcoming these challenges is essential, as predictive maintenance extends beyond conveyor systems and faces broader issues. These include the absence of run-to-failure data, the handling of heterogeneous unstructured data required for machine learning models, and the scarcity of cost-effective sensor and information technologies. This compounds the challenge of employing statistical or machine learning techniques for predictive maintenance. Initial data collected after sensor installation may not comprehensively represent the full spectrum of defects that emerge over time, thus complicating the training of predictive models. Integrating temperature, vibration, and acoustic emission measurements with theoretical estimations remains a multifaceted challenge in achieving maintenance related decision-making.

3 Sustainable Industry 4.0 Approaches

Sustainable manufacturing, a core principle of sustainable development, offers the potential to address challenges, needs, and issues in conveyor belt systems through the integration of Industry 4.0 technologies. By adopting digitalization technologies, big data, cyber-physical structures, virtual reality, and cloud computing, organizations can streamline processes, reduce lead times, and enhance operational efficiency. However, the manufacturing industry faces challenges and risks [19], and to achieve predefined objectives, it's essential to embrace Sustainable Maintenance. This involves aligning profit and strategy goals with decision-making standards that support extended equipment lifecycles and environmental compliance [21]. Leveraging Maintenance 4.0 technologies, organizations can obtain critical data for sustainable maintenance assessment, bridging the gap between sustainability objectives and maintenance practices [22].

At the heart of Industry 4.0 lies the drive for intelligent systems optimizing machine and component uptime [8]. The Internet of Things (IoT) plays a pivotal role in this pursuit, offering adaptability through various protocols and technologies. By integrating devices and machines into intelligent systems, IoT enables real-time diagnostics, proactive environmental responsiveness, and quality control through deep learning, addressing the challenges of maintenance in conveyor belt systems [2]. Aiming to reduce downtime and increase component utilization rates while extending their remaining useful lives, automated fault detection and diagnosis can now gather vast amounts of operational and process conditions data generated from multiple pieces of equipment [20]. This approach not only enhances operational efficiency but also aligns with sustainability goals by reducing waste, energy consumption, and environmental impact through more efficient use of resources.

The exponential growth of data collection and analysis driven by smart manufacturing applications, IoT, and big data has reshaped the manufacturing landscape [9]. Time-series data, valuable for predictive maintenance, takes centre stage. In the context of conveyor belt systems, predictive maintenance is instrumental in preventing unforeseen machinery failures, reducing production downtime, and addressing critical issues. It involves meticulous data analysis to detect impending faults and mitigate risks. The accessibility of low-cost IoT and wireless sensors empowers real-time data acquisition, laying the foundation for data-driven preventive maintenance strategies. The integration of Industry 4.0 technologies in conveyor systems offers the potential to enhance efficiency, optimize maintenance practices, and align with sustainability goals, addressing the needs and challenges in conveyor maintenance. Bondc et al. [9] highlight how Industry 4.0 techniques, particularly the IoT, are revolutionizing predictive maintenance approaches and can provide a solution to conveyor belt system issues while supporting sustainability objectives.

4 Monitoring and Maintenance of Conveyor Belts Using Industry 4.0

This integration of sustainability and advanced maintenance techniques sets the stage for a deeper exploration of approaches in real time monitoring and predictive maintenance to combat the issues faced in conveyor belt systems and overcoming the challenges in implementing them (Fig1).

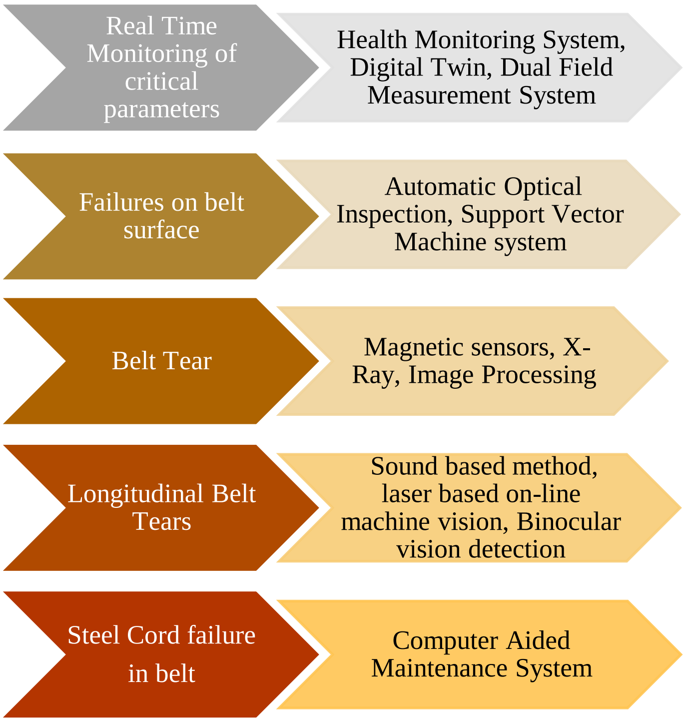

Fig. 1. Issues and sustainable predictive maintenance approaches

4.1 Monitoring of Operating Parameters of Conveyor Systems

Within conveyor systems, the monitoring of operating parameters is essential for ensuring efficiency and sustainability. This section provides an in-depth exploration of the sensors and technologies utilized to track key metrics (Table1). From belt speed to environmental conditions, each parameter plays a crucial role in predictive maintenance and real-time optimization.

Table 1. Monitoring Parameters and Sensors in Conveyor Systems

Parameters	Sensors
Belt Speed	Optical and Magnetic Sensor
Motor Current and Voltage	Current Transformer, Hall-Effect Sensor
Bearing Temperature	Resistance Temperature Detector, Thermocouple
Belt Tension	Load Cell
Vibration Levels	Accelerometer
Material Flow Rate	Flow sensor, Weigh Belt
Belt Alignment	Alignment sensor, laser systems
Drive Torque	Torque Transducer
Environmental Conditions	Temperature, Humidity and Dust Sensor
Energy Consumption	Power or Energy meter

A. Belt Speed: Optical or magnetic sensors are integrated into conveyor systems to ensure precise monitoring of belt speed, facilitating efficient material transportation and preventing overloading or under loading. This capability aligns with the goal of real-time monitoring and predictive maintenance, enhancing sustainability in conveyor operations.

B. Motor Current and Voltage: Current transformers (CTs) or Hall-effect sensors empower conveyor systems to monitor motor health in real time, detecting anomalies like overloading or voltage fluctuations. By enabling predictive maintenance strategies, these sensors reduce downtime, extend equipment lifespan, and enhance sustainability.

C. Bearing Temperature: Resistance temperature detectors (RTDs) or thermocouples enable conveyor systems to continuously monitor bearing temperature, allowing for proactive maintenance interventions to prevent costly breakdowns and promote sustainable practices.

D. Belt Tension: Load cells integrated into conveyor systems ensure accurate and real-time monitoring of belt tension, mitigating issues such as slippage and premature wear. This optimization aligns with sustainability objectives by reducing resource consumption and optimizing conveyor performance.

E. Vibration Levels: Accelerometers monitor vibration levels in conveyor components, detecting anomalies indicative of misalignment, imbalance, or wear. By facilitating predictive maintenance actions, these sensors minimize unplanned downtime and enhance conveyor reliability and sustainability.

F. Material Flow Rate: Flow sensors or weigh belts enable accurate measurement and monitoring of material flow rates, supporting efficient material handling and preventing blockages or jams. This optimization contributes to sustainable practices in material transportation.

G. Belt Alignment: Alignment sensors or laser systems maintain proper belt alignment in conveyor systems, reducing wear on components and minimizing maintenance requirements. This support for efficient and sustainable conveyor operation aligns with optimization goals.

H. Drive Torque: Torque transducers monitor drive torque in real time, optimizing conveyor performance and contributing to energy efficiency and equipment longevity. These sensors enhance sustainability by minimizing resource consumption and optimizing conveyor operation.

I. Environmental Conditions: Temperature, humidity, and dust sensors assess environmental conditions, supporting sustainable conveyor operation by minimizing resource wastage and ensuring a safe working environment.

J. Energy Consumption: Power or energy meters monitor energy consumption, identifying efficiency opportunities and reducing operational costs. By optimizing energy usage, these sensors support sustainability initiatives and enhance overall efficiency in conveyor operations.

4.2 Industry 4.0 Techniques for Real-time Monitoring

Various industry 4.0 techniques to monitor the condition of conveyor systems with respect to the parameters mentioned in the previous sections are discussed below:

4.2.1 Health Monitoring System

Health monitoring systems focus on checking critical machine parameters (like pressure, temperature, and vibration) to detect signs of potential failures [2]. This way, actions can be taken to prevent or mitigate failures before they happen. In this method, three key attributes are monitored: belt speed, weight on the belt, and visual alignment [2].

To implement this, a camera is used to visually monitor the conveyor belt's alignment [2]. For speed and load data, an Allen Bradley PLC is used. The visual data captured by the camera is stored on a local computer, and then analyzed before being sent to the cloud. Data transmission is facilitated using Zumlink™ radio modules, and an IoT gateway helps send the data to the cloud. Once in the cloud, digital data is carefully analyzed to identify patterns and correlations in operating conditions.

This health monitoring approach, as explained by [2], is another example of a methodology developed to keep conveyor systems in good shape. By employing these techniques, maintenance becomes more predictive and effective, contributing to the overall reliability and performance of conveyor systems.

4.2.2 Digital Twin

Digital Twins involve a real-time exchange of information between a physical asset and its virtual representation, forming a two-way connection. This connection is usually established using a network of sensors. One specific methodology related to Digital Twins - the "LIVE Digital Twin" [8]. It follows four main phases: Learn Identify, Verify, and Extend. This approach relies on strategically placing intelligent sensors on a physical asset [8]. A well-developed LIVE Digital Twin can provide intelligent maintenance recommendations by communicating with the real asset and analyzing real-time data.

To establish this connection, sensors and actuators play a crucial role in data collection and asset monitoring. A sophisticated Digital Twin can even predict an asset's Remaining Useful Life (RUL) and suggest maintenance plans. Unlike relying solely on historical data, Digital Twins heavily depend on real-time data and simulations for diagnostics and prognostics [8].

4.2.3 Real Time Material Flow on Belts

Quio et al. introduces an innovative dual-field measurement system designed for real-time material flow measurement on conveyor belts. The system utilizes two light sources, one for the upper and one for the lower surface of the belt, along with two binocular cameras for capturing dual-field contour images. Real-time material flow volume is determined based on belt speed. Unlike conventional visual methods, this approach eliminates the need for preliminary data on the empty belt and is less affected by belt deformation [18].

4.2.4 Automatic Optical Inspection System

Banerjee et al. focuses on designing and implementing an Automatic Optical Inspection (AOI) system to monitor the condition of conveyor belt surfaces. To create this system, three main processes are involved [6]:

Installation and Setup: The inspection assembly and sensors, including a low-cost web camera and a line laser projection device, are set up. This setup captures colour and depth images of the belt surface in a non-intrusive way.

Calibration and Algorithm Development: The sensors are calibrated, and algorithms are developed to achieve specific inspection objectives. This step ensures accurate and meaningful data collection.

Modelling and Optimization: Important inspection factors, like surface illumination, inspection speed, imaging distance, camera frame rate, and camera field of view, are modelled. This helps understand how these factors affect the accuracy of the AOI system.

The process involves using a mixed-level full factorial design of experiment (DoE) approach [6]. This helps to analyze how different control factors (inspection parameters) influence the response factor, which is the measurement error percentage of the AOI system. In essence, this method leverages optics and technology to create a system that visually inspects conveyor belt surfaces. This Automatic Optical Inspection method offers a comprehensive way to assess and maintain conveyor belts by utilizing visual data and meticulous calibration.

4.2.5 Surface Damage Detection System

Prolonged conveyor belt operation and the potential damage from sharp objects create a risk of unnoticed tearing, leading to major accidents. A multi-class support vector machine (SVM) system based on visual saliency employs light sources and CCD cameras for image capture, followed by a decision-making module that coarsely locates and extracts damage [15]. The SVM model quickly identifies damage type and location from salient values. The system delivers real-time responses. Experiments under ideal and wet conditions reveal improved accuracy, especially for tears.

4.2.6 Approaches for Belt Tear & Longitudinal Cuts Detection

A focused exploration of conveyor belt failure factors and tear detection methods reveals the complexity inherent in conveyor belt structures [10]. These complex features make it difficult to identify tears in them and frequently necessitate extra inspection preparation. Non-Destructive Testing (NDT) methods, encompassing sensor-based, X-ray/multispectral-based, and 2D/3D image-based categories, offer diverse approaches for tear detection [10].

A. Magnetic Sensors: Magnetic-based techniques involve coil and magnetized steel cord implementations on various conveyor sections [10]. A distinctive device pre-captures the magnetic field distribution and dynamically contrasts real-time distribution with the recorded version. Deviations beyond a set threshold indicate belt tear.

B. X-Ray: Widely applied for internal image construction and analysis, X-ray detection serves as a prominent NDT method [10]. In essence, X-rays penetrate the conveyor belt, and the received radiation intensity undergoes continuous fluctuations within a fixed range when the belt is intact.

C. Image Processing: The realm of digital conveyor belt images has been revolutionized by sophisticated image processing methods [10]. The inspection system typically comprises image acquisition, pre-processing, and analysis modules. Industrial cameras, lighting sources, and auxiliary equipment form the image acquisition module. Notably, image-based methods provide visualization and comprehensive data due to the utilization of high-speed CCD or CMOS cameras and powerful computers [10].

D. Sound Based Method for Longitudinal Belt Tear Detection: To address accuracy, real-time performance, reliability, and complexity issues in longitudinal tearing detection on belt conveyors, Wang et al. introduced a sound-based method. Sound signals from the conveyors are collected and processed using LFCC and GFCC feature extraction techniques. Convolutional neural networks are trained and optimized with these features, leading to a model for classifying longitudinal tearing sounds. The method operates in real-time, offers a wide detection range, and maintains cost-effectiveness meeting longitudinal tear detection needs.

E. Laser based on-line machine vision detection: Recognizing the need for early detection of longitudinal rips, Xianguo et al. explores an online detection method employing line laser technology and a machine vision system. A red line laser projects onto the conveyor belt's surface, and the corresponding CMOS camera captures and analyzes images to identify rips. The method involves segmenting the red stripe region, obtaining a skeleton representation and binary image, and detecting abnormal pixels using a neighbourhood search method.

F. Bionocular Vision Detection: Integrative Binocular Vision Detection (IBVD) method combines infrared and visible imaging to collect fusion images of the belt [17]. Tear features are extracted using a projection method, enabling the evaluation and identification of potential tears. The IBVD method is experimentally validated, with fusion image processing completed in less than 18 ms, ensuring real-time monitoring [17].

4.2.7 Computer Aided Maintenance Systems

Mazurkiewicz et al. approach to maintaining conveyor systems is through Computer-Aided Maintenance Systems (CMMS). These systems utilize computer techniques to control specific parameters or components that greatly influence the overall reliability of the conveyor system [7]. For instance, a method involving magnetic monitoring is used to assess the condition of the core in steel cord conveyor belts [7]. This approach measures changes in the magnetic field caused by damage to the steel cords in the core. Similarly, specialized sensors placed in the belt, signal damage or wear using transponders. [7].

While this method helps prevent extensive damage and signals belt movement issues, modern transport systems often adopt comprehensive computer-assisted monitoring [7]. Computer tools like CMMS aid in decision-making for maintenance activities, surpassing simple database maintenance functions.

5 Conclusions

The integration of Industry 4.0 technologies and sustainable approaches into conveyor belt systems offers a promising solution to address the critical needs, challenges, and issues that these systems encounter in modern industries. These conveyor systems play a pivotal role in material handling and transportation, making their reliability and efficiency essential for reducing waste, conserving energy, and promoting sustainability. By harnessing advanced sensors, intelligent control systems, and the Internet of Things (IoT), conveyor systems can transition from reactive maintenance practices to proactive real-time monitoring and predictive maintenance strategies. This shift empowers organizations to optimize material flow, minimize product losses, and enhance the overall sustainability and effectiveness of conveyor systems.

Furthermore, the identification of issues such as wear and tear, mistracking, abrasion, sudden longitudinal cuts, and potential adhesion loss in conveyor belt systems stresses the need for predictive maintenance and real-time monitoring. The occurrence of sudden catastrophic failures results in significant downtime, increased maintenance costs, and resource waste. By implementing a comprehensive predictive maintenance system, informed by data collected through real-time monitoring, industries can combat unplanned downtime and extend the lifespan of conveyor systems while promoting sustainability. These advanced techniques, when integrated with Industry 4.0 principles, hold the potential to revolutionize the conveyor maintenance landscape, ensuring the continued efficient and environmentally responsible operation of these crucial systems in modern industry. The research gap in real-time monitoring of conveyor belt system in pursuit of predictive maintenance also stresses the importance of addressing these issues in a sustainable manner. This paves the way for a closer examination of these challenges in implementing sustainable methodologies for real time monitoring of conveyor systems.

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