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Review of the Doctoral Dissertation by Mohammad Siami Araghi, titled.: „Fault Detection Procedures for Belt Conveyor Maintenance Based on AI-Driven Multisource Data Analysis"

1. Basis for the Review

The basis for this review is the letter from the Chairman of the Scientific Discipline Council for Environmental Engineering, Mining, and Energy at Wrocław University of Science and Technology, Prof. Robert Król, dated July 17, 2024 (letter no. RDND08/167/2024). The subject of the review is the doctoral dissertation by Mohammad Siami Araghi, titled "Fault Detection Procedures for Belt Conveyor Maintenance Based on AI-Driven Multisource Data Analysis".

2. Characteristics of the Dissertation

In doctoral dissertation, Mohammad Siami Araghi proposed procedures for detecting faults in belt conveyor idlers based on data fusion from various sources. The doctoral candidate demonstrated that by using RGB images, infrared (IR) images, and acoustic signals, it is possible to develop a complementary and non-invasive method for diagnosing idlers in an extensive belt conveyor system used in the conditions of open-pit mine. His research focused on developing procedures that are resistant to numerous external disturbances present in industrial environments.

The dissertation consists of 8 chapters, a list of figures, a list of tables, a list of abbreviations, and a bibliography. The main text of the dissertation is contained in 111 pages. The theoretical foundation is covered on 32 pages (1-32), while the research methodology and analysis of the results, along with their summary, are presented over 79 pages (33-111). The dissertation includes 61 figures and 12 tables. There are no appendices. The bibliography consists of 146 references. Doctoral candidate is the main author of 3 of them. The dissertation was written in English.

From an editorial standpoint, the reviewed work is written in a professional manner, its structure is correct, and I did not note any major editorial errors during my reading. The entire dissertation is concise, accurate, and clearly written, with a consistent chapter structure. There is no repetition of content, which is a significant advantage. The dissertation is based on a collection of internationally recognized scientific articles.

In the introduction (Chapter 1), the doctoral candidate described the main motivation for his research, highlighting the current needs of the mining industry related to the automatic monitoring of idlers, and presented the main objectives of the dissertation and its organization.

Chapter 2 provides an analysis of the state of knowledge in the relevant research area. The issues of idler failure, different types of idler damage, various maintenance strategies used in past decades, and the development of robotic applications for conveyor infrastructure inspection tasks are discussed. In this chapter, the author also presents the results of a literature review on the application of IR image processing methods, both classical and AI-driven. The chapter also addresses advances in the field of multisensor information fusion.

Chapter 3 is dedicated to the application of IR imaging methods for condition monitoring using robotic solutions in mining environments. The author proposed an innovative approach to image classification, utilizing deep learning to detect overheating idlers. For this purpose, a combination of histogram analysis techniques and binary classification methods based on convolutional neural networks (CNN) was employed. The theoretical foundations of the methods used in processes such as region-based fault detection in IR images, region of interest estimation, IR image color transformation and normalization, noise reduction in images, and hotspot and anomaly detection are presented. The architecture of the neural network proposed for binary image classification is also discussed. In this chapter, the doctoral candidate emphasizes the challenges and opportunities of the proposed region-based fault detection approach in IR images. The potential applications of the method in robotic solutions are also addressed.

In Chapter 4, the author proposes an innovative approach to assessing the technical condition of conveyor idlers based on IR images, which overcomes current challenges in U-Net architecture related to significant imbalance and shortage of training samples. The author suggests utilizing a pre-trained CNN VGG16 architecture to distinguish relevant features from preprocessed IR image samples, which were obtained through an inspection robot. In the next step, using RF and XGBoost methods, he developed a procedure for categorizing the extracted features and detecting anomalies in the analyzed image samples. The developed procedures serve as feature classifiers, which were then applied to perform semantic segmentation tasks on captured IR images. Subsequently, the doctoral candidate combined unsupervised PCA and k-means algorithms to reduce the dimensionality of the data samples and group them based on their significance and the final classification of segmented thermal anomalies present in the obtained IR images. As a result, he demonstrates that the proposed methodology is effective and provides precise categorization of thermal anomalies into distinct classes. Additionally, it is worth emphasizing that the doctoral candidate, by using real data obtained during the inspection of a conveyor operating in an open-pit mine, proves the usefulness of the proposed mathematical models in semantic segmentation and the diagnosis of the technical condition of conveyor idlers.

In Chapter 5, the doctoral candidate proposes the use of an original method of multisensor information fusion for non-invasive monitoring of the conveyor idlers condition.. The author correctly notes that the accuracy of data collected in the challenging environmental conditions of an open-pit mine may be periodically limited. For this reason, he proposes data fusion from various sources, such as audio signals, RGB and IR images, to fill in the information gaps caused by measurement errors or noise. Due to the rotational nature of idler operation, he correctly highlights the need to apply cyclostationary analysis in processing audio signals. In Chapter 5, the author presents a method for imaging idler bearing fault signatures using a spectral coherence map. Additionally, he conducted a comparative study focused on selecting the most effective CNN models used for classifying idler conditions based on audio signals and RGB images. In the research, 8 CNN architectures were tested. The final decision-

making process is based on information obtained from all available diagnostic data sources. For this purpose, the author proposed a dynamic weighted majority voting ensemble method. At this stage of processing, the weight of each classification model is continuously adjusted for each sample. The process also considers the surface temperature of the idler, defined based on IR images. According to the doctoral candidate, the approach based on information fusion from various sources is more effective than monitoring a single parameter, which is confirmed by practical industrial applications in both open-pit and underground mining.

In accordance with the standards of scientific writing, the author dedicated Chapters 6 and 7 to discussing the following:

1. The materials and equipment used in the research (primarily the inspection robot equipped with a sensory layer).
2. The research experiments and their execution to collect data.
3. The metrics used to evaluate the proposed methodologies.
4. The results of the experiments.
5. The validation of hypotheses established for each research question from Chapters 3, 4, and 5, namely the effectiveness of the proposed methods in assessing the technical condition of idlers used in conveyor transport.

Additionally, Chapter 7 presents the author's critical evaluation, where he clearly articulates the strengths and weaknesses of the proposed methods.

Chapter 8 provides a summary and final conclusions, along with the author's reflections on potential future research directions.

3. Evaluation of the Doctoral Dissertation

Belt conveyors are critical assets used for material transportation across various industrial sectors. The efficient and safe management of conveyor networks determines the continuity and scale of production throughout the entire technological process. Therefore, it is essential to support maintenance staff in inspecting conveyor systems, which typically consist of extensive networks spread over large areas. One critical aspect involves the failure of idlers that support the belt on which material is transported. Damaged idlers can increase resistance along the conveyor route, leading to higher energy consumption, improper belt operation, its wear, and, in extreme cases, fires. For these reasons, regular inspection of idlers is necessary, requiring the observation of each idler along routes that often exceed several kilometers. Additionally, modern monitoring methods are crucial since early stages of idler damage are usually undetectable by the senses of operating personnel. It should also be emphasized that inspecting a running conveyor poses a risk of accidents and is both time-consuming and costly. Moreover, due to the high cost of continuous monitoring installations along the conveyor route and the expense of maintaining them, such solutions are usually applied only to critical components, often limited to drums and drives.

Given this context, the doctoral candidate's the proposed usage of an inspection robot and the developed diagnostic methods are essentially important, timely, and useful both scientifically and practically.

The doctoral candidate investigated the impact of conveyor components and environmental conditions on interference and detection errors. He proposed comprehensive validation procedures that significantly improve the segmentation of collected signals and the detection of fault-related patterns. It is noteworthy that he employed the latest machine learning methods, which in most cases are only beginning to be used in the mining industry. Due to algorithm

limitations before 2014, efficient feature recognition was not feasible because of the limitted capabilities of these algorithms. As a result, convolutional architectures could not be successfully integrated beyond two layers. In short, advancements in deep learning have opened new possibilities for AI-driven algorithms, especially in applications that are challenging from a classification task perspective. One such challenge is the assessment of the condition of the rotating components of a belt conveyor operating in an open-pit mining environment.

In classical two-stage recognition, the focus is on identifying when a given parameter (e.g., temperature) exceeds a strictly defined decision threshold. Belt conveyors operating in the condition of open-pit mining work under varying external loads and in the presence of numerous sources of interference. Throughout the year, ambient temperatures is characterized by significant amplitude. Additionally, the operating conditions, design features, and purpose of each conveyor can differ significantly. For these reasons, the performance of traditional methods may be limited. Many articles in the scientific literature describe the use of classical approaches, but many of these studies are conducted under controlled conditions in the lab. The fact is that there are many unpredictable events can occur, which may complicate the diagnostic process and, in many cases, lead to inconsistent decisions from inference algorithms. In his research, the doctoral candidate draws attention to their presence several times, proposing validation procedures. Although they may seem overly developed, they demonstrate the complexity of the process of automatic diagnosis of the idler condition. The doctoral candidate rightly focused his research on validating different sources of thermal radiation and acoustic sources, which create challenges in extracting diagnostic features for the idlers.

Furthermore, an important achievement of the doctoral candidate is addressing the current issue in technical diagnostics related to unbalanced industrial data sets. In practice, most components of the inspected machine operate correctly, and emerging malfunctions are quickly repaired during routine maintenance work. As a result, obtaining a comprehensive diagnostic database with a sufficient number of signals from faulty components is very time-consuming, often extending beyond the timeframe of the research project. Consequently, the collected diagnostic database contains a significantly larger number of negative (healthy) cases than positive (faulty) ones, which ultimately impacts the algorithms' diagnostic capabilities. It should be emphasized that methods commonly used in practice – statistical methods, traditional machine learning methods, or deep learning – are not resilient in such cases. Facing this issue, the doctoral candidate proposed a practical solution to the class imbalance problem using an outlier detection filter. He automated the procedure for detecting and eliminating unnecessary (negative) samples, generating a dataset consisting only of positive samples. In the next step, the algorithm significantly reduced the redundancy of negative samples to facilitate the successful training of deep learning models, thereby reducing the computational complexity of model training. The developed method is based on outlier detection. Thermal anomalies were defined as hotspots in the extracted frames. As an effective anomaly detection method, the doctoral candidate proposed the use of the IQR statistic.

The proposed decision-level information fusion approach ensures fault detection at various stages of development and is resilient to the low number of positive samples. The author highlights several directions for further development of the methods using the inspection robot. One such direction is the use of satellite navigation (GNSS) and LIDAR to map the conveyor route and locate damaged idlers on the map. He also points out the potential of LIDAR for conveyor fault detection. The author emphasizes the significant potential of inspection robots,

which in the near future will be able to replace humans in performing inspection tasks in difficult and hazardous industrial environments.

The advantage of the developed methods is the reduction in the cost of obtaining diagnostic information and improving their precision. With the use of robotics, human resources can be delegeted to tasks that increase the overall production capacity of the enterprise. A significant achievement of the doctoral candidate is the experimental confirmation of the effectiveness of the developed methods for classifying idler conditions based on industrial data.

4. Originality of the Dissertation and Assessment of the Doctoral Student's Theoretical Knowledge

The research conducted by the doctoral candidate addresses the complex issue of detecting conveyor idler damage at various stages of the degradation process. The candidate has performed an extensive literature review in the area of conveyor maintenance in the mining industry, idler degradation, and diagnostic methods. He has identified factors influencing measured diagnostic signals and the limitations of traditional two-state diagnostic approaches. Essentially, despite many studies on idler diagnostics, there has been a lack of comprehensive elaborations presenting a holistic methodology for idler inspection in industrial conditions. Much of the available literature relies on statistical methods where studies were conducted under controlled conditions in the lab. Consequently, it is challenging to assess their effectiveness and resilience to a range of stochastic events, non-stationary conveyor operating conditions, diverse constructions. Moreover, most methods are based on infrared images, which are not optimal for early damage detection, as idler temperature increases typically occur later in the degradation process. For this reason, the candidate correctly emphasizes the need for the development of methods based on the fusion of information from many sources. He has proposed the use of a robot, which enables full automation of the conveyor infrastructure inspection process. The proposed solution is based on non-invasive data acquisition using three data sources: RGB images, infrared images, and acoustic signals. It should be noted that the proposed robotic system is one of the first solutions using Industry 4.0 technologies. Currently, modern mining enterprises are moving away from complex diagnostic systems due to their complexity and high costs of implementation and maintenance. The methods proposed by the candidate focus on minimizing information acquisition costs and achieving full automation. The dissertation suggests that these methods could also be applied to manual measurements performed by supervisors during conveyor inspections or maintenance actions. Therefore, it can be anticipated that with minor modifications, they could also be adapted for use in other industry sectors, including underground mining. In my opinion, the doctoral dissertation represents an original and practical solution for supporting the management of belt conveyor networks.

It should be emphasized that currently in the industry there are still cases where the process of diagnosing idlers is based on subjective impressions of maintenance personnel obtained through the senses. Many damages are thus ignored, leading to unplanned stappages. By adopting a systematic and scientific approach to diagnosing idler fault, mining companies will be able to enhance productivity, profitability, and operate in accordance with sustainable development principles.

In my opinion, a significant achievement of the doctoral candidate is the application of modern and advanced signal processing and deep learning methods based on data fusion from different sources. Many of them were developed only a few years ago and had not previously

been applied to idler diagnostics. Currently, the diagnostic system is in its early stages of development. However, it is important to highlight that the use of artificial intelligence-inspired methods allows for continuous improvement of the system during its operation and adaptation to specific cases. The developed methods do not require the potential user to possess specialized knowledge in diagnostics, AI, or signal processing. Comprehensive validation and classification procedures are performed fully automatically and consider a range of factors affecting the measured signals. The use of data fusion ensures inference in situations where one of the data sources is incorrectly measured or does not provide diagnostic information. The candidate correctly focused on validating various sources of thermal radiation or acoustic sources that pose challenges in extracting diagnostic features for idlers. The developed validation methods are robust in these situations. Data fusion enables early detection of bearing damage, overheating, and blockage of the idler. **The research methodology is characterized by a significant level of cognitive advancement and can be considered a significant scientific achievement.**

The developed diagnostic database represents an interesting research resource for modeling idler degradation processes and predicting damages. Despite years of experience in using belt conveyors in industry, the area of their predictive maintenance has not been developed enough. Thus, the dissertation presents an innovative approach to the investigated issue that may meet current expectations of belt conveyor users. The developed analytical models enable the performance of unique experiments and provide a broad insight into the ongoing degradation processes of the idlers. In my opinion, the research work has expanded the current state of knowledge on the subject. The potential of the proposed analytical tools has been verified by the candidate using real data.

Therefore, it can be concluded that the reviewed doctoral dissertation by Mohammad Siami Araghi represents an original solution to the scientific problem of conveyor idler diagnostics. In addition to the dissertation, the research has been presented in many articles in international scientific journals and conference materials. According to the Scopus database, the candidate is the author of 4 papers in journals listed in the Philadelphia list, cited a total of 16 times. The candidate notes in the dissertation that he is a co-author of 4 journal articles, 4 conference papers, and 6 conference papers presenting an abstract. All papers are related to the subject addressed in the dissertation. His current Hirsch index in the Scopus database is 2.

Considering the scientific and cognitive value of the dissertation, as well as the current publication achievements, I conclude that **doctoral candidate Mohammad Siami Araghi demonstrates comprehensive theoretical knowledge in the area of belt conveyor operation, which falls within the discipline of environmental engineering, mining, and energy.**

5. Detailed Remarks

The doctoral candidate has undertaken a significant research issue in the area of conveyor transportation operations. He assumed that by utilizing data fusion from various sources, it is possible to diagnose idlers in the presence of different disturbances occurring in open-pit mining environments. It is important to recognize the challenges associated with acquiring knowledge and data by the candidate, who is not an employee of the mine. Below I am listing some observations which, I consider non-critical but potentially useful for the candidate in future research.

As mentioned earlier, the structure of the dissertation is well-organized and logical. The distribution of content across the chapters is appropriate. I noted a few editorial and language errors, all of which have been highlighted in comments on the provided PDF file for correction before potential issue of the dissertation.

In Chapter 2, the author presents a simplified construction of the idler set. In my opinion, there is a lack of description regarding the construction of individual idler and bearing.

In Chapter 3.3, which deals with Region of Interest (ROI) estimation, the author mentions that there are various methods for estimating ROI but does not describe any of them. Ultimately, it is not known what method the Author used or whether it was determined manually.

In Chapter 3.4, concerning IR images color transformation and normalization, the author describes a method for converting color IR images (3 channels) to grayscale (1 channel). Typically, this is done by combining corresponding values from each channel, multiplied by an appropriate coefficient. In practice, a coefficient of 0.33 is generally used for the red, blue, and green channels. However, the candidate employed a different methodology heavily oriented towards the blue color. In the dissertation I did not find information about the reason for such a selection of parameters.

In Chapter 3.10, the candidate presents the binary classification architecture. The author introduces a CNN-based model for binary classification of frames into those containing an overheated conveyor idler and those that do not. However, the choice of parameters for this model is not justified within the dissertation. It is unclear whether any parameter optimization was conducted.

In Chapter 6.4, the candidate presents a summary of the collected IR data in the table. There was a lack of similar descriptions for the collected RGB images and acoustic signals. The author mentions that over 20,000 thermal imaging frames were collected, but the number of samples described later in the section with results fluctuates around a few hundred. The reason for this reduction in sample size is not clear. A comprehensive table detailing the amount of data used for training each model was also missing. In the future, it is also recommended to obtain a larger data sample, because neural networks using high number of parameters require significant amount of data in order to train and operate effectively.

Additionally, regarding model validation, it was not obvious whether a separate test sample was used for all models. Some tables, such as Table 7.6, clearly indicate that they refer to the test sample. However, for results presented in Section 7.1, it was uncertain whether they refer to the test sample or the validation sample (used for validation during training).

Furthermore, the author proposed three methods for processing IR images (Chapters 3, 4, and 5), each using different procedures and algorithms. In the data fusion scheme, I was unable to identify which procedures were used..

A minor drawback of the dissertation is the lack of a broader description of the measurement methodology. While the dissertation addresses the development of diagnostic methods, it is not clear what conditions need to be met to obtain reliable input data. It was unclear whether measurements should be performed under external load of conveyor and how long after its start-up. In the future, extending the measurements to both healthy and damaged idlers from the moment of conveyor start-up would be a valuable addition. Additionally, significant annual temperature fluctuations are observed in open-pit mines. It is recommended to test the developed methods under industrial conditions during different times of the year.

6. Other Remarks

Figure 3-1, which illustrates the stages of idler damage development and the diagnostic symptoms observed during these stages, lacks a reference to the bibliography. It is unclear whether this figure results from the candidate's own research or if it was inspired by another work.

Graphs comparing data from healthy and damaged idlers should have consistent axis ranges (e.g., Figure 3-4 and Figure 5-3).

Several times the candidate incorrectly used the term "conveyor belt system" instead of "belt conveyor system," and "conveyor belt idler" instead of "belt conveyor idler." On another occasion, the term "belt conveyor joint" was used instead of "conveyor belt joint."

When citing several works from the bibliography in chronological order, the candidate provides each citation number separately in square brackets. It would be sufficient to provide the range of cited references from N to M.

The description of collected data in the methodology seems redundant, as it is also provided in the experimental section.

On page 84, the fragment "(..) The non-Gaussian behavior in the audio signal is caused by the mechanical belt joints, which are metallic clamps used to connect two pieces of the belt. While in operation, the belt moves along the rolling idlers. When the mechanical clamp comes into contact with a specific idler, it creates a sudden impulsive noise due to the metal clamp striking the metallic coating of the idler (...)" seems to be an unnecessary repetition of previously explained content.

Punctuation was not used in sentences containing formulas.

7. Final Conclusion

Considering the comprehensive nature of the research conducted both theoretically and practically, as well as the objectives achieved by the dissertation, I positively assess its scientific and cognitive value. I believe that the candidate has addressed a current and significant issue within the scientific discipline of environmental engineering, mining, and energy. Additionally, I confirm that the reviewed doctoral dissertation by Mohammad Siami Araghi **meets the requirements** set forth in the applicable Act of July 20, 2018 – Law on Higher Education and Science (Journal of Laws of 2023, item 742). Therefore, I recommend to the Council of the Scientific Discipline of Environmental Engineering, Mining, and Energy that the dissertation be accepted and approved for public defense.

In summary of the evaluation of the reviewed doctoral dissertation, I conclude that it represents an original solution to the research problem addressed. The candidate demonstrates a strong knowledge of issues related to belt conveyor systems, data analysis, and technical diagnostics. The remarks provided do not, in any way, diminish the value of the doctoral dissertation. In my opinion, the presented research results already have significant practical value.