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REVIEW of the doctoral dissertation

Prepared by **M.Sc. Mohammad Siami Araghi** entitled ***Fault Detection Procedures for Belt Conveyor Maintenance Based on AI-Driven Multisource Data Analysis***, prepared at the request of the Chairman of the Scientific Discipline Council of Environmental Engineering, Mining and Energy at the Wrocław University of Science and Technology on July 17, 2024. Supervisors of the doctoral dissertation: Prof. Dr. Hab. Eng. Radosław Zimroz and Prof. Dr. Hab. Eng. Tomasz Barszcz

I. Thesis motivation

The dissertation focuses on automation in mining. Regular inspections of moving belts and idlers are necessary to prevent the risk of fire. SCADA systems typically monitor other elements of belt conveyors. In order to reduce the risk of accidents and human errors, especially in hazardous environments, automatic solutions are being implemented. Advanced inspection robots equipped with sensors and cameras can carry out these tasks. The challenge lies in developing algorithms for identifying damage in challenging mine conditions. Artificial intelligence methods, particularly rapidly advancing deep neural network models, are valuable in this regard. This work aligns with the concept of Industry 4.0 and is in line with current global trends.

II. General characteristics of thesis

The doctoral thesis comprises 138 pages, with the substantive part and bibliography totaling 124 pages. The remaining part includes the title page, abstracts in English and Polish, table of contents, a list of 61 figures, a list of 12 tables, and a list of abbreviations. The work cites 146 publications directly related to the subject and scientific methods used.

The dissertation contains eight chapters. In the first chapter, the author justifies the motivation for undertaking the subject of the work. He formulates the objectives of the doctoral dissertation, presents the further organization of his dissertation and presents a list of publications of which he is a co-author.

In the second chapter, the applicant conducts a literature analysis of issues related to belt conveyor operations, especially those used in mines, and characterizes their failures. The text presents inspection robots used in mines for monitoring and analyzes the applications of images recorded with an infrared camera. It delves into the issues of infrared image processing using artificial intelligence, specifically deep neural networks CNN. The chapter concludes with a literature analysis on the fusion of information from multiple sensors.

In Chapters 3 and 4, the author presented two different approaches for detecting anomalies in infrared images: Region-based Fault Detection (Chapter 3) and Semantic Segmentation (Chapter 4). In Chapter 3, the he described the methods for preprocessing, segmentation, and classification.

In Chapter 4, the author focuses on the models of deep neural networks used, namely CNN and U-Net with different variants. The chapter also introduces the transfer-learning approach and classification methods using RF and XGBoost models. It characterizes the use of the pre-trained VGG-16 network. Additionally, the author proposes methods for augmenting the IR image database and an unsupervised method for clustering IR images.

In Chapter 5, you can find the proposed methodology for utilizing all three signals (IR and RGB images and audio signals) to diagnose the state of idlers. This chapter provides information about methods for expanding the RGB image database and audio signals, as well as details on data preprocessing methods, feature extraction, and classification.

Chapter 6 describes the experiment, provides hardware and software specifications, characterizes the data sets and defines the indicators used for evaluation. Chapter 7 contains the research results and their discussion. The last chapter is the conclusions and prospects for further work.

III. Evaluation of PhD thesis

The doctoral thesis is interdisciplinary, covering topics within the field of engineering and technical sciences. I believe that the work falls within the scientific discipline of *Environmental Engineering, Mining and Energy* due to the monitored objects and the selection of sensors, diagnostic signals and data acquisition methods characteristic of mine operation.

The doctoral thesis was meticulously written using appropriate technical language to describe various analyzed processes, phenomena, and technologies. The work is enriched with clear tables and well-chosen graphic illustrations. The structure of the work is clear, although there are excessive subchapters and sub-sub-chapters, some of which are very short. For instance, subchapters 4.5, 5.6, and 5.7 contain only one sub-sub-chapter each.

The literature review is well-developed, reflecting the current state of knowledge and referring to the latest research worldwide on the problems discussed in the dissertation. It's worth mentioning that the author is up-to-date with the latest trends in machine learning for image processing, despite the rapid development of AI models. In the second chapter, the applicant analyzes the literature concerning the topic, and I would like to find reports on the analysis of the audio signal used in the work in this chapter. The brief information I was seeking is included in subsection 5.2.*Audio Signal Preprocessing*, along with relevant literature items from this area.

The author didn't create a traditional thesis for their doctoral dissertation. Instead, they outlined the challenges they encountered and described their contributions to solving them. Their goal was to develop a method for detecting faults in idlers of a belt conveyor in an opencast mine. The location of the mining site was crucial as it influenced equipment selection, communication, and algorithms. To achieve this, the author utilized a specially designed inspection robot, a microphone, and RGB and IR cameras to capture signals and images. The

main focus of the work was on signal processing procedures using AI methods, particularly deep machine learning. The applicant showcased various preprocessing methods to improve image segmentation capabilities and presented two alternative approaches to segmentation: region-based segmentation and semantic segmentation. They also developed a unique semantic segmentation technique using a deep CNN architecture and a machine learning-based approach.

The advantage of this work is that the methods were tested in real industrial conditions, as opposed to the usual laboratory settings for experiments on belt conveyors. The author had to tackle real-world challenges such as extracting useful signals in the presence of ambient noise, dealing with dust that hinders image analysis, and working with too few signals recorded for a damaged object. The author chose appropriate hardware and software tools to accomplish the tasks in the specific conditions of an opencast mine and also established evaluation criteria for the developed methods.

One interesting aspect of this work is addressing a common challenge in machine operational diagnostics: unbalanced databases. The author outlined methods for enhancing databases, focusing on RGB and IR images, as well as audio signals, which is crucial for utilizing deep neural networks. Additionally, he selected machine learning algorithms that don't require extensive amounts of data to function effectively, such as transfer learning models.

An additional interesting aspect is data clustering using unsupervised learning methods such as Principal Component Analysis (PCA) and K-means. This could serve as a foundation for creating an unsupervised anomaly detection method.

The author focused mostly on deep neural network models. I am unsatisfied with the limited coverage of audio signal analysis methods.

I believe that developing a heterogeneous information fusion method based on knowledge about the occurrence of symptoms of idler failure over time is a significant achievement of the dissertation. In my view, the key to addressing this issue lies in Fig. 3.1, which depicts the evolution of failure in belt conveyor idlers. Instead of being included in Chapter 3, I think it would have been more suitable to include it earlier, in Chapter 2.

The author conducted numerous simulation studies using deep machine learning to compare evaluation metrics for various classification models. He provided a thorough analysis of the measurement results and compared the latest findings with both previous ones published by himself and with other cited works.

I believe that the results achieved constitute a significant contribution to the development of engineering and technical sciences. I assess the activities presented in the work positively in terms of content and method. The author correctly carried out literature research and properly planned and executed the scientific experiment. He developed methods for processing signals/images using deep machine learning models for diagnostic purposes in industrial conditions.

IV. Critical remarks and questions

When reading the dissertation, several specific questions arise:

1. *Figure 3-1: Evolution of failure in belt conveyor idlers.* – Is this the author's own research or is it taken from the literature?

2. Page 41: There is "*In grey-scaled IR images, the total number of available levels for pixel L spans into* **[0, 256].**" Should it be: "…[0, 255]"? Or considering formula 3.10, "…[1, 256]"?
3. Fig. 4.9 (p.62): Are W_{object} and H_{object} in the following description W_{defect} and H_{defect} in Figure 4.9? What do *i* and *j* in formula (4.7) and in Fig. 4.9 represent?
4. Fig.4.10: Was the defect centralization successful in the third case?
5. Formula (5.8), p. 80: What are the meanings of t_{max}, t_{min}, and t_{input}? Do they represent temperatures, and what are their corresponding values? What values does the weight t_j reach?
6. Formula (5.9), p.80: What is S_j? How does the value of the G index change?
7. Isn't the size of the set of spectral coherence maps (8 items) for analysis in Fig.7.14 too small to conclude on this basis?
8. Did the author investigate the effect of lighting on the quality of image segmentation, especially RGB (see Fig.6-1)? How can lighting conditions be unified?
9. How many features were obtained for IR, RGB and audio maps as a result of the feature extraction procedure?
10. Preprocessing is very important. In Figure 3.4 on page 40, a histogram analysis is conducted to determine the best method. It is observed that dark pixels dominate the histogram, and interesting bright regions are close to 0. How can it be determined if the histogram has been adjusted for bright pixels? Normalization methods enhance the contrast of dark areas in the image, but how do they affect areas showing hotspots?

V. Editorial notes

The dissertation is written clearly, with a few editorial comments:

1. The work is excessively divided into subchapters and sub-sub-chapters, some very short. For example, subchapters 4.5, 5.6 and 5.7 each have one sub-sub-chapter.
2. The abbreviations lack explanation: IR, RGB. However, the abbreviation Random Forest- RD is a typo (it should be RF).
3. Fig. 5.2 and 5.3 description of the X axis: Modulation Frequency – no unit.
4. Chapter 3 and subchapter 3.2 have the same title "Region-based fault detection in IR images", and subchapter 3.2 is only one of 10 subchapters constituting about 10% of chapter 3. It should have a more detailed title.
5. In formulas 3.5, 3.6, and 3.8, instead of „d^2" there should be "σ^2".

Final conclusion

The submitted dissertation by MSc. Mohammad Siami Araghi, entitled *Fault Detection Procedures for Belt Conveyor Maintenance Based on AI-Driven Multisource Data Analysis*, provides an original solution to the scientific problem of developing a non-contact monitoring and diagnostic system for identifying damage to belt conveyor idlers in a mining environment. The author solved the problem by selecting appropriate hardware and software and conducting experimental studies. The assumed goals of the doctoral dissertation were fully achieved.

The author has shown a sound theoretical understanding of the construction and operation of belt conveyors in mines, methods for operating these devices, the causes of their damage, and the construction and operation of machine monitoring systems. They have also demonstrated impressive skills in developing algorithms for advanced signal and image processing methods and in independently planning experimental studies. The work falls within the scientific disciplines of environmental engineering, mining, and energy. The critical and editorial comments presented in the review only point out minor shortcomings or seek clarifications, and do not diminish the essential value of the work or its significance for practical applications.

The doctoral dissertation of MSc. Mohammad Siami Araghi fulfills all the requirements specified in *art. 187 ust.1 i 2 ustawy z dnia 20 lipca 2018 r. – Prawo o szkolnictwie wyższym i nauce (Dz.U. z 2023 r., poz.742).* The presented results of analyses, experimental studies, and image-processing algorithms are original. The achieved results hold practical significance and can be applied in belt conveyor monitoring systems, not only in mines.

My assessment of the work is positive. I request that Mr. Mohammad Siami Araghi be given the opportunity to publicly defend his doctoral thesis.

Ivona Lamorska