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The review of the
Doctoral dissertation
„WEHICLE DIAGNOSTICS USING ARTIFICIAL INTELLIGENCE AND DIGITAL SIGNAL PROCESSING METHOD"
By Muhammad AHSAN

The review was performed on the basis of a contract for specific work no. UMC/1292/2025 dated 24/04/2025 between me and the Silesian University of Technology in Gliwice. The basis for concluding the contract is the resolution of the Disciplinary Council "Control, Electronics, Electrical Engineering and Space Technologies" of the Silesian University of Technology. The subject of the doctoral dissertation falls within the scope of the discipline "Control, Electronics, Electrical Engineering and Space Technologies. The dissertation was carried out in the Department of Measurements and Control Systems, Faculty of Automatic Control, Electronics and Computer Science, Silesian University of Technology in Gliwice. Its supervisor was Prof. Pol. Śl. Dariusz Bismor, PhD, DSc, Eng.

The doctoral dissertation of MSc Eng Muhammad Ahsan is written in English. It has 155 pages. It is divided into 6 chapters, the first of which is the Introduction presenting the subject of the dissertation, and the last one is its Conclusion. The dissertation also includes 6 appendices, numbered from A to F, and a list of references including 126 items, including 8 co-authored by the Candidate. The scientific achievements, including 4 articles in journals and 4 conference papers, has been presented in a separate list. The dissertation contains 87 figures in the main part and 20 in the appendices, as well as 19 tables in the main part and 1 in the appendices. The lists of figures and tables precede the main part of the dissertation. The dissertation also contains acknowledgments and abstracts in Polish and in English. There is no list of acronyms used.

In the first part of Chapter 1, the Author presents the background and motivation for undertaking the subject. They are related to the need to improve the diagnostics of vehicle drive system failures. Methods based on digital signal processing and artificial intelligence are being developed. The signals that are the basis of these modern diagnostic methods are vibration signals of the engine operation. Appropriate instrumentation is needed to record and pre-process the vibration signal, as well as advanced algorithms for signal analysis, machine learning and identification. I consider the subject of the dissertation to be important both scientifically and utilitarian. After selecting the scope of the dissertation, the Author conducts a review of the literature on the subject. This review is divided into three parts. The first part concerns hardware: MEMS accelerometers and embedded platforms. The capacitive accelerometer ADXL1002 manufactured by Analog Devices and the Beagle Bone Black platform were selected for further work. The second part presents methods for diagnostics of the drive system based on digital processing of the vibration signal. The methods based on analysis of the signal's time course (Peak Value, RMS, Crest Factor, Kurtosis), analysis of the frequency spectrum (FFT, Envelope Spectrum ES, Spectral Kurtosis SK) and the most advanced time-frequency methods (Short Time Fourier Transform STFT, Wavelet Transform WT, Empirical Mode Decomposition EMD, Hilbert Huang Transform HHT, Wigner-Ville Dristribution WVD) are briefly presented. The third part briefly describes artificial intelligence methods: Artificial Neural Networks (ANN), Convolutional Neural Networks (CNN), Deep CNN: DCNN and DCNN Long-Short-Term Memory (DCNN-LSTM). In the next part of Chapter 1, the Author formulates the objectives of the work. They are the creation of an appropriate database of measured vibration signals, designing appropriate digital filters to extract the desired information from the recorded signals, identification and diagnosis of misfire and diagnosis of the bearing condition using selected DSP methods as well as misfire diagnostics using AI algorithms. At the end of Chapter 1, the structure of the dissertation is presented.

Chapter 2 describes the hardware used for the research. It consists of the ADXL1002 MEMS accelerometer and the BeagleBoneBlack development platform. The chapter describes the basic properties of both modules, while their detailed technical data can be found in appendices A and B. The author's task was to integrate both modules, calibrate them, and test them for vibration data collection and their initial processing. In this way, a highly efficient measuring tool was obtained. The chapter is not scientific in nature, but engineering. This is not a reproach. A scientific work in the field of technical sciences must include an engineering part, which is a necessary introduction to further activities of a strictly research nature. Both the ADXL1002 accelerometer and the BeagleBoneBlack platform are commercial tools available on the market, and their integration is also an engineering activity. This activity requires high qualifications and was performed by the author excellently.

Chapter 3 presents the methods and types of measurement data using the system described in Chapter 2. Data were acquired for different modes and different engine operating conditions. These were engine speeds of 1500 RPM (25 Hz), 2500 RPM (41.667 Hz) and 3000 RPM (50 Hz), at no load, and at half and full load, and data were also collected from a healthy engine and under misfire conditions. The next subchapter presents other vibration datasets known from the literature for bearing diagnostics. These are: IMF Test-to Failure Vibration Dataset developed at the Center for IMS at the University of Cincinnati and MFPT Bearing Fault Dataset located in the database of the Society for Machinery Failure Prevention Technology (MPTF). Bearing diagnostics is one of the main issues discussed in Chapter 4, where digital signal processing (DSP) methods are used for diagnostic purposes.

Chapter 4 is the first chapter in which the Candidate presents his research results on vibration diagnostics of vehicle engines. Chapter 4 presents Digital Signal Processing methods. These methods are used for bearing diagnostics and engine misfire diagnostics. In bearing diagnostics, the basic task is to extract the vibration signal frequencies that are caused by bearing damage. They are extracted using advanced algorithms such as HSA – Harmony Search Algorithm and PSO – Particle Swarm Optimization. For the analysis with HSA, the Author used parameters and characteristics such as Spectral Kurtosis (SK) and Short-Time Fourier Transform (STFT), while the PSO method uses Continuous Wavelet Transform (CWT). The lack of use of the vibration signal cepstrum is noteworthy. Cepstral analysis is often used for bearing diagnostics. The author of the dissertation mentions it only once in passing in subsection 1.2.2 on page 13. The author implemented, programmed and conducted optimization studies of band-pass filters using the HSA algorithm for the purpose of bearing fault diagnostics. The optimization concerned the detection of the filter's center frequency, its bandwidth and order. Simulation studies were conducted on IMS data sets containing signals with Fundamental Train Frequency and Output Race faults and on MFPT data sets of bearings with Output Race (OR) faults. In the further part of Chapter 4, the author describes the PSO algorithm implemented by him for the optimization of ARL (Asymmetric Real Laplace) - Wavelet BPF and simulations conducted with its use of OR and first and second baseline fault detection of signals from the MFPT data set. A significant increase in the signal-to-noise ratio was obtained, which allowed for the detection of envelope spectrum fault frequencies. Engine misfire is manifested by changes in the frequency and amplitude of vibrations. Time and frequency analysis of the signal is used to detect them using DSP. These include FFT, Envelope Spectrum ES and Spectral Kurtosis SK. More complex methods include STFT or wavelets and EMD (Empirical Mode Decomposition). The method based on IMF (Intrinsic Mode Function) using the above characteristics for misfire diagnostics was implemented by the Author and described in section 4.5. The signals for analysis were obtained from vibration measurements with an ADXL1002 accelerometer with a BeagleBone Black card. In section 4.6. The Author conducted a critical comparative analysis of the implemented methods in terms of their ability to detect damage. The research confirmed the usefulness of the HSA and PSO methods for optimizing band-pass filter parameters, which allowed for reducing the SNR and contributed to increasing the efficiency of bearing damage detection. FFT was not a very effective tool for misfire identification. A significant improvement was achieved using ES. However, EMD turned out to be the best tool. The Author's research showed the usefulness of DSP methods for diagnosing vehicle engines.

In Chapter 5, the Candidate presents methods for diagnosing a vehicle engine using artificial intelligence. The diagnostic methods presented only concern misfire fault. Author describes various AI models in the introduction. He uses in practice Deep Convolutional Neural Networks (DCNN), DCNN-Long Short Term Memory (DCNN-LSTM) and Multi-Kernel-DCNN-LSTM. Subsequent algorithms are improvements of the original DCNN model, allowing for increasingly efficient diagnosis The Author uses recordings obtained using the MEMS ADXL1002 accelerometer and the BeagleBoneBlack platform as data sets. These recordings are subjected to preprocessing, which consists of processing the recordings using EMD, which results in obtaining a set of components called IMFs (Intrinsic Mode Functions), their segmentation, which results in a 1D data set in the time domain, and converting the 1D sets into 2D sets presented in grayscale, and visualizing the segments using *t*-distributed Stochastic Neighbor Embedding (t-SNE). Details (Python codes) for 1D to 2D data conversion are presented in Appendix D, and the t-SNE software implementation (also in Python) is presented in Appendix E. I consider this procedure justified, because 1D-2D data conversion and visualization are only tools used for diagnostic purposes. The data set consists of 4 different engine states: engine without misfire, and engine with misfire for 1500 RPM (25 Hz), 250 RPM (41, 67 Hz), and 3000 RPM (50 Hz). Each of these states contains 882400 data points. Diagnostics was performed on both 1D and 2D data sets. In the case of data not subjected to training using AI models, the visualization of t-SNE segments results in a mixed set of points, which does not allow for making a diagnosis.

In the successive subsections, the Author describes the use of increasingly advanced AI models. The structure of these subsections is the same. The implementation of the model is presented in the form of a block diagram, a table with parameters of subsequent blocks as well as an execution algorithm. Then, the simulation results are presented along with their discussion.

In the following, I will focus on the research results, without referring to the structure of the algorithms. The research was conducted for the one-dimensional (1D) and two-dimensional (2D) models described above. Each test consisted of 10 independent runs. Aggregated data including the maximum, minimum, and average accuracy and standard deviation for the 10 runs and all types of data are presented in the table. The complete results for the 10 runs are presented in Appendix F. The accuracy of the algorithm on the training and test data is also presented in a bar chart. As expected, the accuracy on the training data always reaches 100%. In the following, the speed of the algorithm's approach to the final results is presented as a dependence of the accuracy on the number of epochs of the algorithm's operation. Then, the detailed results are presented in tables, in which accuracy, sensitivity, specificity, balanced accuracy, and geometric mean accuracy are placed. These quantities are defined in the text. The results were given for the signal without fault, "healthy" and damaged for the rotational speeds of 1500, 2500 and 3000 RPM. The Author also presented these results on bar graphs. The analysis of the results also includes the confusion matrix including the numbers of correctly and incorrectly diagnosed faults. The diagnostic ability of the algorithm was also presented in the form of visualization of *t*-SNE segments. If the sets of points for individual tests presented on these graphs are separated, this indicates high diagnostic ability.

In Chapter 5.4 the DCNN model is tested, in Chapter 5.5 the DCNN-LSTM model, and in Chapter 5.6 the multi-Kernel DCNN-LSTM model. A comparative analysis of the results obtained as a result of the operation of individual algorithms was performed in Chapter 5.6. It was shown that even the simplest DCNN algorithm has a high diagnostic ability. The average accuracy on the 1D data set was 92.01%, and on the 2D set – 97.61%. For the DCNN-LSTM algorithm, the corresponding accuracies were 94.70% and 97.95, and for the most extensive multi-Kernel DCNN-LSTM algorithm 96.97% and 99.32%. As can be seen, the accuracy increases with the complexity of the algorithm. An interesting issue is the cost of each algorithm. The author addresses this issue by comparing the work of algorithms for 1D and 2D data sets. Increasing the accuracy (or more generally – quality) for 2D data is of course more expensive, because a conversion step from 1D to 2D data is required. I do not know, however, whether a small increase in accuracy justifies the use of more complex algorithms. In conclusion, the Author has demonstrated the great potential of artificial intelligence methods for diagnosing faults in vehicle engine drives.

The last, 6th chapter of the work contains a summary of the achieved results. It is largely a repetition of the conclusions that can be found at the end of each chapter. This is also the structure of chapter 6. In parts 6.1 and 6.6 of the chapter, the Author presents the results achieved during the adaptation of the ADXL1002 accelerometer and the BeagleBoneBlack card to tasks related to the main topic of the work. As I mentioned earlier, the use of the accelerometer and the card for specific tasks that are the subject of the dissertation is an engineering aspect, not a scientific one. In my opinion, the Author devotes a disproportionate amount of attention to it. However, I understand the Author who, it seems, devoted a lot of effort to this issue. The conclusions regarding the use of DSP and AI for vehicle engine diagnostics are a repetition of the conclusions that can be found in the main chapters of the dissertation, i.e. in chapters 4 and 5. The conclusions that summarize the entire dissertation can be found in chapters 6.5-6.8. Chapter 6.5 presents a comparative analysis of the developed methods. DSP-based diagnostic methods are an excellent tool for detecting simple faults, but in more complex situations they show significant limitations. Then, better results are obtained using AI methods, especially the multi-Kernel-DCNN-LSTM algorithm. The author points out that this method has great possibilities, especially in combination with the signal preprocessing method, such as EMD. In subsection 6.7, the author concludes that he draws attention to the possibilities related to the use of multisensor techniques with the participation of traditional piezoelectric accelerometers. There are also possibilities to use more efficient computational algorithms.

After the main part of the work, it consists of appendices A-F, which contain supplementary material used during the work, the inclusion of which in the main part would disrupt the logical flow of the argument. In particular, appendix F contains a complete set of results obtained during 10 runs of individual AI models, i.e. DCNN, DCNN-LSTM and Multi-Kernel DCNN-LSTM. In the main part of the dissertation, only the most representative results are presented, on the basis of which conclusions are drawn. I consider such a procedure justified.

The doctoral dissertation of MSc Eng Muhammad Ahsan concerns a scientific issue of great practical importance. It uses the latest methods and algorithms of signal processing and artificial intelligence for diagnostics of vehicle engines. Detection of defects and damages at an early stage of their occurrence prevents serious damages, leading to destruction and also dangerous to the life and health of people. The results achieved in the dissertation can be implemented at a low cost. The scientific results achieved are partially published, others are being prepared for publication. The work is written in correct language, and the flow of argument is coherent and logical. It is easy to read, which is especially important when presenting issues that are not easy and simple at all. I did not find any significant errors, mistakes or ambiguities in it.

On page 17, 4th line from the bottom, the phrase noise-to-signal ratio appears. It is usually used in reverse order: signal-to-noise ratio (SNR). Was this intentional?
On page 85, in the caption of Figure 5.2, instead of 2500 ROM it should be 2500 RPM.

The only serious flaw of the dissertation, of an editorial nature, is the lack of a list of acronyms. The author used a great many acronyms, which was also reflected in my review. Some of them are widely known and used, but many are related to specific issues. They are usually explained in the text of the dissertation, usually once. If such an acronym appears multiple times in the rest of the dissertation, searching for an explanation in the text is burdensome.

To sum up, the doctoral dissertation of mgr inż. Muhammad Ahsan entitled "Vehicle Diagnostics using Artificial Intelligence and Digital Signal Processing Methods" confirms the general knowledge of the PhD student in the discipline of "Automation, Electronics, Electrical Engineering and Space Technologies" and the ability to independently conduct scientific work. The subject of the doctoral dissertation is an original solution to a scientific problem and an original solution in the field of applying the results of own scientific research in practice. Thus, the dissertation meets the requirements of art. 187 sec. 1-2 of the Act "Law on Higher Education and Science", and therefore I apply for the admission of the PhD student to further stages of the doctoral procedure. I include the dissertation in the category "Meeting the requirements with a clear excess, deserving of distinction". Therefore, I also submit a motion for the dissertation to be distinguished.

Wrocław, June 3, 2025