# Modern ICT and Mechatronic Systems in Contemporary Mining Industry

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**Abstract.** The paper deals with modern ICT techniques and systems, and mechatronic systems for mining industry, with particular attention paid to results achieved by the authors and their research groups. IT systems concern process and machinery monitoring, fault detection and isolation of processes and machinery, and assessment of risk and hazards in mining industry. Furthermore, innovative applications of AI methods are addressed, including pattern recognition and interpretation for process control, classification of seismic events, estimating loads of conveyors, and the others. Special attention is paid to applications of mechatronic solutions, such as: unmanned working machinery and longwalls in coal mines, and specialised robots for basic work. Mobile robots for inspecting areas of mines affected by catastrophes are presented, too. Moreover, recent communication solutions for collision avoidance, localisation of mining machinery, and wireless transmission are addressed. The paper concludes with most likely development of ICT and mechatronic systems for mining industry.

**Keywords:** ICT in mining industry · Risk and hazards assessment · Mechatronic working systems for mines · Robotized inspection

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## 1 Motivation

Mining industry is experiencing technological and organizational revolution in recent years. There are several pan-European initiatives supporting such changes (European Innovation Partnership on Raw Materials, European Insitute of Innovation and Technology - Raw Materials Branch, EURobotics with Topic Group "Robotics in Mining", etc.) [11–13]. It motivates us to highlight current trends in mining industry and present several research activities exploiting very advanced technologies (rarely recognized as mining applications). Depending on type of mined raw materials, used technology, environmental hazard, etc., mining companies might face very different problems. For the needs of this paper we will use several perspectives. The first critical feature is type of a mine (opencast, underground). Next critical issue is energetic or non-energetic type of materials. The first one is mainly related to hard coal mined in general in underground mines with explosive atmosphere. The second one, at least in Poland, is associated with underground mines and deeply located copper ore deposits. A deep underground mine means hard rock with extremely harsh environmental conditions, natural hazard (seismic risk) and relatively poor automation of mining operations (room and pillar technology, no mechanical excavation in contrast to longwall systems in underground hard coal mines). Relatively easier case could be noticed in open cast mines (lignite brown coal or non-energetic raw materials including aggregates). There are examples of nearly fully automatic mines with central room control, autonomous machines, analytic centre, etc. Regardless of mentioned issues in all cases motivation to introduce advanced technology to the mining industry is very similar. To be competitive enough, a mining company should be economically effective, safe and environment-friendly. Nowadays, mining companies are great examples of advanced technology users. Big mining companies like Codelco, Rio Tinto, KGHM, etc., use advanced IT technologies (monitoring of objects and processes, data modelling for processes optimization, decision support systems, reporting tools etc.), advanced process control systems, robots for inspections or partially robotized mining operation (drilling/bolting, transport, etc.) and many other smart solutions. In this paper we address modern ICT systems and mechatronic (and especially robotic) systems. The discussion illustrated by selected real world examples will cover underground hard coal mines, opencast lignite mines and deep underground copper ore mines.

## 2 IT Systems in Mining Industry

The diversity of IT systems in the mining industry is vast and covers many areas of current activity of the company. Some of them are very general (electronic document circulation, purchasing, finance management, etc.) and have been implemented in the past [4,9,16]. However, specific solutions dedicated to production monitoring management in mining are non-trivial and their successful application is challenging for many companies. The most prominent examples are SCADA systems used to monitor condition of machines, process, environment, seismic activity and many others.

The authors are especially involved in developing methods and systems for fault detection of machinery and for assessment of risk and hazards. As an example, the *Disesor* system is presented which is a decision support tool for fault diagnosis, hazard prediction and analysis in mining industry [29]. The Polish consortium leaded by the EMAG Institute of Innovative Technology together with the Silesian University of Technology, Warsaw University and Sevitel Sp. z o.o. has developed the system. *Disesor* is a shell system that can be filled in with data and facts concerning a given problem domain. It can deal with fault diagnosis in different plants (processes or machinery), and with hazard prediction and analyses of such phenomena as e.g. methane hazard in coal mines, or rock burst hazard in underground mines. The architecture of the system consists of: a Data Repository, Data Preparation and Cleaning module, Prediction Module, Analytical Module and Expert System Module. The core of Analytical, Prediction and Expert System modules is based on *RapidMiner* platform [15,26]. The goal of the Data Preparation and Cleaning Module, which is referred further as ETL2, is to integrate the data stored in data warehouse and process it to the form acceptable by the methods creating prediction and classification models. In other words the ETL2 module prepares training sets. The Prediction Module is aimed to apply classification and prediction models created in the Analytical Module for a given time horizon and frequency of the values measured by the chosen sensors. This module also tracks the trends in the incoming measurements. Created predictive models are adapted to the analysed process on the basis of the incoming data stream and the models learnt on historical data (within the Analytical Module). The module provides interfaces that enable the choice of quality indices and their thresholds that ensure the minimal prediction quality. If the quality of predictions meets the conditions set by the user, the predictions will be treated as values provided by a *virtual sensor*. They can be further utilised e.g. by the Expert System but also can be presented to a dispatcher of a monitoring system. The Expert System module is aimed to perform on-line and off-line fault diagnosis of machinery and other technical equipment. It is also capable of supervising processes and supporting the dispatcher or expert by decision-making with respect to both technical condition of the equipment and improper development of the process. The Expert System allows reasoning by means of multi-domain knowledge representations and multi-inference engines. The inference process is performed by means of classical inference based on Boolean logic or fuzzy inference system as well as probabilistic inference with the use of belief networks. The Analytical Module is aimed to perform analysis of historical data (off-line) and to report identified significant dependencies and trends. The results generated by this module are stored in the repository only when accepted by the user. Therefore, this module supports the user in decision-making of what is interesting from monitoring and prediction point of view. It also provides additional information that can be utilised to enrich the knowledge base of the Expert System or that can be utilised to comparative analysis. The module supports identification of changes and trends in the monitored processes and tools and it also enables to compare the operator's and dispatcher's work.

The more detailed description of the system can be found in [21,29]. Examples of applications of this system to practical mining problems will be presented in the tutorial. Moreover, the authors also view *Disesor* as a tool that can be used for a wider spectrum of applications, and therefore it is considered to apply this software for solving similar problems/tasks [19].

Other examples concern brown coal mines, where giant bucket wheel excavators and belt conveyors systems are of special importance to the operation of a mine. Researchers from Wrocław University of Technology have developed a monitoring and diagnostic system with original decision making scheme for the case of nonstationary operating conditions (variable load/speed) [1,8,35]. This system includes instrumentation technology, signal processing, diagnostic procedures and maintenance strategies for drive units (gears, bearings) as well as for belts with steel cords. Unique, original solutions have been also developed for complex multistage planetary gearbox.

The next application concerns a belt conveyor network, which is distributed over large area and can include up to 100 conveyors with many components to monitor. Implementation of online monitoring system on each of them might be considered as expensive. Thus, another solution for underground mine has been developed. It assumes that data will be acquired on demand by a portable system. The central part of this solution is related to CMMS system for simple support of maintenance stuff. The personnel needs to be informed when and what should be checked. Measurements require minimum skills, data processing is fast and decision is available immediately. A key issue is long term monitoring of objects behaviour and extracting appropriate knowledge from population of machines of the same type but with different condition [31].

The last example is related to load-haul-dump (LHD) machines: loaders, trucks, drilling and bolting machines. The most difficult issues here are: complexity of the machine (more than 70 variables are monitored), its mobility, extremely harsh environment (these machines are working in mining face area), and number of machines in operation. KGHM Cuprum has been a partner in the SYNAPSA project focused on monitoring LHD machines. It has been implemented in the deep underground mines in KGHM "Polish Copper" S.A. Again, holistic view on instrumentation (on-board monitoring system, wireless communication, fiber optics network, data warehouse) and advanced analytics and reporting tools were developed in this project, which is described e.g. in [36].

## 3 Artificial Intelligence Applications

Artificial Intelligence (AI) methods and applications have become ever more and more popular in the mining industry. One of the most frequently applied are pattern processing, analysis, recognition and interpretation methods. As a pattern we understand an ordered set of data, including images collected by video and infrared camera systems. There are many applications of pattern recognition (PR) techniques for detecting faults basing on process data and residual signals.

One prominent example of using AI is diagnostics of machinery. Based on measured data (vibration, temperature, pressure, etc.) one needs to make a decision regarding machine condition. In the most of cases it is two-class classification (good/bad condition). Such an approach requires appropriate training data sets that cover both good and bad condition cases. Unfortunately, mining machines are often very specialised, designed on demand, for the particular mine (see for example a bucket wheel excavator). No diagnostic tests are allowed (introducing artificial damages to learn about behaviour of machine in bad condition). In such a case, the so called *one-class classification* could help [2,27]. Mining machines are working in time varying conditions, including also transients. It means that apart from classical diagnostic features there is a need to use descriptors of operational conditions (speed or load values). It leads to data fusion, multidimensional, multivariate data analysis. Again, fundamental problems arise (are data representative, are they redundant, can dimensionality be reduced, are there feaures dependent linearly or nonlinearly, etc.). Some of these issues have been discussed in [2,3,5].

PR can be also applied to detect and classify seismic events. Monitoring of seismic events is operating 24 h 7d. Till now from the mining perspective the energy and localisation of a seismic event is automatically evaluated by the monitoring system. By appropriate parameterisation of a seismic signal it might be possible to recognise automatically the character of a seismic event. It has been shown by Xu *et al.* [33] that spectral representation of different types of seismic events is significantly different and can be the basis for classification. Such a classification for copper ore mine was discussed by Sokołowski *et al.* [30].

Very important AI applications concern data mining (DM) in databases collected by multiple systems employed in the mining industry. Data carries very useful information of relations between process parameters, the state of the plant (object or process) and outputs. There are multiple systems developed to acquire knowledge from data in an automatic way, with the *Disesor* system [29] as a prominent example. But knowledge engineering is not limited to DM applications only. For example, the *Disesor* system provides a bunch of tools for acquiring knowledge from domain experts, which can then be implemented in a dedicated Expert System capable of supporting the user (operator, diagnoser, manager) in taking decisions concerning further development of the process under control [29]. It is well-grounded that expert systems can be effectively applied in many areas such as medicine, education, entertainment, risk management and fault diagnosis [7,23]. The present activity of scientists and engineers confirms that expert systems also play very important role in the field of mining engineering. In [34] the authors present an expert system for supervising workstations of coal mines. This system applied production rules to express knowledge, whereas the inference process was realized by means of forward as well as backward reasoning. A safety management system for coal mine was suggested in [32]. The authors created the information processing system that was based on web site technology. This system is used in Zibo mining industry group and Xu Chang coal plants in China. The authors of [14] developed an expert system for assessment and optimization of coal mines in terms of their eco-efficiency. This was not a typical expert system, but rather a set of software tools for managing a mining company. The more detailed and deeper survey on expert systems for aiding the mining industry may be found for instance in [6].

Another area of application of AI (in particular machine learning – ML) in mines is hazard assessment and prediction. For example the *Disesor* system enables predictions of two types of hazards: methane and seismic ones [29]. In case of methane hazard the system predicts a maximum methane concentration at a longwall end area. The prediction horizon is medium-term (several minutes). An accurate medium-term prediction of maximum methane concentration would let the mine dispatcher monitor labour security factors in a more efficient way, which would result in reduction in the number of costly automatic power switch-offs caused by overrun of the admissible methane concentration level. One of the main tasks of coal mine geophysical stations is to determine the current state of seismic hazard (particularly, hazard of high-energy destructive tremor which may result in a rockburst) in underground mining places. Rockbursts, as phenomena related with mining seismicity, pose a serious hazard to miners and can destroy longwalls and the equipment. The *Disesor* system predicts the value of the seismic energy which will be emitted within the longwall area. Higher ($> 5 \cdot 10^5$ J) energy values are treated as potentially dangerous situations.

In both the cases ML methods are used to construct predictive models. Due to the imbalanced nature of the data (dangerous situations are rare) the problem of constructing good predictive models characterised by good sensitivity and specificity is difficult [18]. For this reason there were organized two international data mining competitions [17] in order to develop the methodology for predictive models suitable for the problems mentioned above. The best models are based on an advanced data pre-processing and the use of ensemble classification paradigm. The best methods were implemented within the *Disesor* system. The implementation includes: tuning the model to conditions existing in the specific longwall and monitoring the quality of predictions (by setting minimum thresholds related to wrong decisions) and concept drift identification.

Bearing in mind the current state of the art in this subject it can be concluded that recent challenges for mining companies cause that advanced expert systems are viewed as indispensable decision support tools which are being more often involved in their activities. The authors of the paper still see the need for development of more advanced expert system shells that can be successfully applied in the mining industry [25]. Their studies focus on the practical applications of such software tools for solving different problems such as fault diagnosis of belt conveyors [20] or longwall shearers [28], hazard prediction [21], etc.

## 4 Mechatronic Systems and Robotics

Much effort has been made since decades to release human miners from carrying out very heavy and unsafe work. In the paper we address the most impressive systems such as unmanned working machinery and longwalls. There are two different approaches to releasing human operators from direct operation of machinery working in hazardous environment. The first one consists in equipping the machinery with the option of *remote control*. The operator can remain in a safe place (and in the best solution need not to go down to the underground part of the mine) and control the operation of the machinery basing on information provided by video and other sensory systems [10]. Moreover, an expert system can support him by taking decisions. The more advanced technology consists in completely autonomous operation of the machinery, which requires significantly higher intelligence of the system. Autonomous and remote controlled systems are also offered for mining trucks, bulldozers, drills, and shovels [22].

Very broad research and applications concern copper ore mining industry, where its good communication infrastructure facilitates remote operation of machinery.

To make a next step in robotisation one should consider specialized autonomous robots for basic work including automated drilling machines, automated machinery for loading blasting holes, autonomous LHD (loaders and trucks), robotized arms for oversized copper ore lumps crushing, etc. Currently in KGHM "Polish Copper" S.A. such projects are in progress and results are expected in near future. Also some works related to inspection robots (flying, walking, etc.) are considered for spatially distributed infrastructure inspection. As mentioned earlier, it is not reasonable to monitor online everything in a large scale mine. To minimise humans effort one might exploit mobile robots (in teleoperation mode or fully autonomous). Since it is very difficult to develop a machine that deserves absolute autonomy despite instant situation in an operating scene, a very innovative approach of *virtual teleportation of the operator to the operational scene* is developed and implemented (the key know-how of SkyTech Research Sp. z o.o.).

Other group of mechatronic systems is devoted to robotized inspection. Such systems can release human inspectors from very hazardous and troublesome work. An example of this can be inspection of an area of coal mine affected by a catastrophe such as fire, explosion of gases, etc. An exemplary system called *TeleRescuer* [24] replaces human rescuers in inspections of roadways closed by a dam, since it is capable of operating in explosive atmosphere and in increased temperatures. The system is composed of two main parts: a mobile robot satisfying ATEX M1 requirements, and an innovative Human-Machine Interface (HMI) that can evoke virtual teleportation of the operator to the scene where just the robot operates, but the rescuer could not be there due to unacceptable hazard to his life. Although the main operation mode is remote control, the system is capable of operating autonomously in case of losing communication with the control station located in a fresh-air base. This research is carried out by a consortium where Silesian University of Technology (Poland) acts as the leader, and the partners are: VSB – Technical University of Ostrava (Czech Republic), the University Carlos III of Madrid (Spain), SkyTech Research Sp. z o.o. (Poland), Simmersion GmbH (Austria), and KOPEX S.A. (Poland). More details of this system will be presented in the tutorial.

## 5 Sensing and Communication

Collision avoidance and proximity detection systems become ever more and more popular in the mining industry. The reason is that mobile mining machinery becomes bigger and operates with higher speeds of its organs, while there remain significant dead sight areas where the operator is unable to detect other machines or even humans. The collision avoidance systems are based on RFID, radar, vision or ultrasonic systems. Their operation is affected by harsh environment conditions such as high relative humidity, dust or coal culm.

Other essential issue concerns communication. If one considers coal mines, the coal itself that constitutes walls and ceilings of a roadway affects propagation of radio waves. Nonetheless, countable wireless communication systems are developed, capable of working in underground coal mines. The complexity of the system depends on data transfer rate required to transmit measurement results and images. Recently wireless systems capable of operating in coal mines take advantage of a network of repeaters based on motes – simple communication modules that can organize themselves in an 'ad hoc' network. Such a system is developed in the framework of *TeleRescuer* project playing the role of a backup communication system for the robot.

## 6 Conclusions

In the paper some issues concerning ICT and mechatronic systems that are used nowadays in mining industry have been discussed. Development of such systems can have great influence on the further evolution of this industry. If one considers increasing the productivity by simultaneous reduction of costs and hazards, then intensive automation with the goal to develop autonomous machines that might totally replace human operators is the answer. Nevertheless, it is impossible to isolate completely the human operator from supervising the system in some rare, yet very critical situations when automatic control cannot assure flawless operation. To this end, the innovative *virtual teleportation technology* could help by allowing remote intervention of the experienced operator who personally could assess the situation and find solution to the problem unsolvable by the autonomous system itself. The next step could be to include a *self-learning functionality* to the system to allow collecting new skills that could be used in the future to operate when facing problems too difficult to solve until now. Such ambitious goals can be undertaken by international consortia and require both the R&D and implementation work. Research centres and universities can play very important role in this process by developing new methods and demonstrators. Very close collaboration with the industry would be of great importance.

## References

1. Bartelmus, W., Zimroz, R.: Vibration condition monitoring of planetary gearbox under varying external load. Mech. Syst. Signal Proc. **23**(1), 246–257 (2009). Special Issue: Non-linear Structural Dynamics

2. Bartkowiak, A., Zimroz, R.: Outliers analysis and one class classification approach for planetary gearbox diagnosis. J. Phys. Conf. Ser. **305**(1), 012031 (2011)
3. Bartkowiak, A., Zimroz, R.: Dimensionality reduction via variables selection - linear and nonlinear approaches with application to vibration-based condition monitoring of planetary gearbox. Appl. Acoust. **77**, 169–177 (2014)
4. Brzychczy, E.: The intelligent computer-aided support in designing mining operations at underground hard coal mines. In: 23th World Mining Congress, August 11–15 2013, Montreal (2013)
5. Cempel, C.: Multidimensional condition monitoring of mechanical systems in operation. Mech. Syst. Signal Process. **17**(6), 1291–1303 (2003)
6. Chekushina, E.V., Vorobev, A.E., Chekushina, T.V.: Use of expert systems in the mining. Middle-East J. Sci. Res. **18**(1), 1–3 (2013)
7. Cholewa, W.: Expert systems in technical diagnostics. In: Korbicz, J., Kowalczuk, Z., Kościelny, J., Cholewa, W. (eds.) Fault Diagnosis, pp. 591–631. Springer, Heidelberg (2004)
8. Cioch, W., Knapik, O., Leśkow, J.: Finding a frequency signature for a cyclostationary signal with applications to wheel bearing diagnostics. Mech. Syst. Signal Process. **1**(38), 55–64 (2013)
9. COIG. http://www.coig.pl/en/mining, (as of Aug. 2016)
10. CSIRO. Mining safety and automation. http://www.csiro.au/en/Research/EF/Areas/Coal-mining/Mining-safety-and-automation, (as of Aug. 2016)
11. EC-Europa. https://ec.europa.eu/growth/tools-databases/eip-rawmaterials/en/content/strategic-implementation-plan-sip-0, (as of Aug. 2016)
12. EIT. http://eitrawmaterials.eu/, (as of Aug. 2016)
13. EU-Robotics. https://eu-robotics.net/, (as of Aug. 2016)
14. Golak, S., Wieczorek, T.: Koncepcja system ekspertowego do oceny i poprawy ekoefektywności kopalń (in Polish). Studia Informatica **116**(2), 213–222 (2014)
15. Hofmann, M., Klinkenberg, R.: RapidMiner: Data Mining Use Cases and Business Analytics Applications. Chapman & Hall/CRC, Boca Raton (2013)
16. IBM. http://www-935.ibm.com/industries/metalsmining/, (as of Aug. 2016)
17. Janusz, A., Sikora, M., Wróbel, L., Stawicki, S., Grzegorowski, M., Wojtas, P., Slezak, D.: Mining data from coal mines: IJCRS'15 data challenge. In: Yao, Y. (ed.) RSFDGrC 2015. LNCS, vol. 9437, pp. 429–438. Springer, Heidelberg (2015). doi:10.1007/978-3-319-25783-9_38
18. Kabiesz, J.: Effect of the form of data on the quality of mine tremors hazard forecasting using neural networks. Geotech. Geol. Eng. **24**(5), 1131–1147 (2006)
19. Kadlec, P., Gabrys, B., Strandt, S.: Data-driven soft sensors in the process industry. Comput. Chem. Eng. **33**(4), 795–814 (2009)
20. Kalisch, M., Przystałka, P., Timofiejczuk, A.: A concept of meta-learning schemes for context-based fault diagnosis. In: XV International Technical Systems Degradation Conference, TSD International Conference, Liptovsky Mikulas, 30 March – 2 April 2016, pp. 113–114 (2016)
21. Kozielski, M., Sikora, M., Wróbel, Ł.: *Disesor* - decision support system for mining industry. In: Ganzha, M., Maciaszek, L., Paprzycki, M. (eds.) Proceedings of the 2015 Federated Conference on Computer Science and Information Systems, vol. 5 of Annals of Computer Science and Information Systems, pp. 67–74. IEEE (2015)
22. Leica Geosystems. Autonomous and remote controlled mining. http://mining.leica-geosystems.com/news/all-news/autonomous-and-remote-controlled-mining, (as of Aug. 2016)
23. Liebowitz, J.: The Handbook of Applied Expert Systems. CRC Press LLC, Boca Raton (1997)

24. Moczulski, W., Cyran, K., Januszka, M., Novak, P., Timofiejczuk, A.: *Telerescuer* - an innovative robotized system for supporting mining rescuers by inspecting roadways affected by catastrophes. In: 24th World Mining Congress (2016)
25. Przystałka, P., Moczulski, W., Timofiejczuk, A., Kalisch, M., Sikora, M.: Development of Expert System Shell for Coal Mining Industry. Springer, Heidelberg (2016)
26. RapidMiner: *RapidMiner* software website, August 2016. https://rapidminer.com/
27. Sáez, J.A., Krawczyk, B., Woźniak, M.: Analyzing the oversampling of different classes, types of examples in multi-class imbalanced datasets. Pattern Recogn. **57**(C), 164–178 (2016)
28. Sikora, M., Moczulski, W., Timofiejczuk, A., Przystałka, P., Ślęzak, D.: DISESOR: An integrated shell decision support system for systems of monitoring processes, equipment and hazards. In: Mechanizacja, automatyzacja i robotyzacja w górnictwie, pp. 39–47 (2015)
29. Sikora, M., Przystałka, P., (eds.): Zintegrowany, szkieletowy system wspomagania decyzji dla systemów monitorowania procesów, urządzeń i zagrożeń (in Polish). Publishing House of the Institute for Sustainable Technologies, National Research Institute, Radom, Poland (2016) (in print)
30. Sokołowski, J., Obuchowski, J., Madziarz, M., Wyłomańska, A., Zimroz, R.: Features based on instantaneous frequency for seismic signals clustering. J. VibroEng. **18**(3), 1654–1667 (2016)
31. Stefaniak, P., Zimroz, R., Bartelmus, W., Hardygóra, M.: Computerised decision-making support system based on data fusion for machinery systems management and maintenance. Appl. Mech. Mater. **683**, 108–113 (2014)
32. Wang, C., Wang, Z.: Design and implementation of safety expert information management system of coal mine based on fault tree. J. Softw. **5**(10), 1114–1120 (2010)
33. Xu, X., Dou, L., Lu, C., Zhang, Y.: Frequency spectrum analysis on micro-seismic signal of rock bursts induced by dynamic disturbance. Min. Sci. Technol. **20**(5), 682–685 (2010)
34. Yingxu, Q., Hongguo, Y.: Design and application of expert system for coal mine safety. In: Second IITA International Conference on Geoscience and Remote Sensing (2010)
35. Zimroz, R., Hardygóra, M., Błażej, R.: Maintenance of belt conveyor systems in Poland - an overview. In: Proceedings of the 12th International Symposium Continuous Surface Mining - Aachen, pp. 21–30. Springer, Heidelberg (2015)
36. Zimroz, R., Wodecki, J., Król, R., Andrzejewski, M., Śliwiński, P., Stefaniak, P.: Self-propelled Mining Machine Monitoring System - Data Validation, Processing and Analysis. Springer, Heidelberg (2014)