DOI: 10.32056/KOMAG2020.2.6

Mechatronic systems developed at the KOMAG

Krzysztof Stankiewicz

KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

e-mail: kstankiewicz@komag.eu

Keywords: mechatronic systems, control algorithms, electrical systems, communication systems

Słowa kluczowe: systemy mechatroniczne, algorytmy sterowania, systemy elektryczne, systemy komunikacyjne

Abstract:

Intelligent control and automation systems, capable for adaptation and learning, are expanding their area of application in industrial practice. Particularly, due to the necessity of continuous improvement of work safety, as well as the need to increase production efficiency and work reliability, the group of users of intelligent systems, which are currently implemented in many important branches of Polish industry, including mining, is constantly growing. The KOMAG Institute of Mining Technology develops modern, intelligent and distributed mechatronic systems which increase work safety and reduce energy consumption of technological processes. Innovative solutions of distributed control and power supply systems, focused on improvement of selected technological processes are presented in this article. Assumptions of IIoT (Industrial Internet of Things) and direct machine communication M2M (Machine to Machine) have a large impact on the structure and functionality of control systems, shaping the ideas of Industry 4.0. All control systems, compatible with IIoT, use communication networks, often of high complexity, combining various components, modules, actuators and sensors. KOMAG researchers have noticed and proposed a solution to the problem of self-organized communication paths in a complex sensor network. In order to create and optimize the communication structure, the SA class algorithm (Swarm Algorithm) was proposed. As an example of a distributed control system, the KOGASTER control system using the CAN communication bus was described. Another innovative solution, presented in the article, is Shield Support Monitoring System (SSMS), which allows monitoring the condition of the powered roof support in real time by monitoring its operating parameters (such as geometry, hydraulic pressure parameters and tip to face distance). SSMS provides data for the Longwall Mining Conditions Prediction System (LMCPS) in order to forecast the risk of a dike and generate information on necessary corrective actions. The projects developed at the KOMAG perfectly fit into the current development trends of mechanization and automation systems for the industry, including the mining industry.

Streszczenie:

Inteligentne systemy sterowania i automatyki, zdolne do adaptacji i uczenia się, zyskują coraz szersze grono użytkowników i powiększają obszar zastosowań w praktyce przemysłowej. Jest to szczególnie uwarunkowane potrzebami ciągłego polepszania bezpieczeństwa pracy, a także zwiększaniem wydajności produkcji i ciągłości pracy w wielu ważnych gałęziach polskiego przemysłu, w tym w górnictwie. Instytut Techniki Górniczej KOMAG rozwija nowoczesne, inteligentne i rozproszone systemy mechatroniczne, które wychodzą naprzeciw tym oczekiwaniom jednocześnie zmniejszając energochłonność procesów technologicznych. W artykule przedstawiono innowacyjne rozwiązania rozproszonych systemów sterowania i zasilania, ukierunkowane na usprawnienie wybranych procesów technologicznych. Założenia IIoT (Industrial Internet of Things) i bezpośredniej komunikacji maszyn M2M (Machine to Machine) mają duży wpływ na strukturę i funkcjonalność układów sterowania maszyn, kształtując przy tym idee Przemysłu 4.0. Wszystkie systemy sterowania, kompatybilne z IIoT wykorzystują sieci komunikacyjne, często o dużej złożoności, łączące różne komponenty, moduły, siłowniki i czujniki. Specjaliści ITG KOMAG dostrzegli i zaproponowali rozwiązanie problemu samoorganizacji ścieżek komunikacyjnych w złożonej sieci czujników. W celu stworzenia i optymalizacji struktury komunikacyjnej zaproponowano algorytm klasy SA (ang. Swarm Algorithm). Jako przykład rozproszonego systemu sterowania opisano system sterowania KOGASTER wykorzystujący magistralę komunikacyjną CAN. Innym nowatorskim rozwiązaniem, przedstawionym w artykule, jest System Monitorowania Zmechanizowanej Obudowy Ścianowej (SSMS, ang. Shield Support Monitoring System), który pozwala na monitorowanie jej stanu w czasie rzeczywistym poprzez monitorowanie wybranych parametrów (takich jak geometria, ciśnienia hydrauliczne i odległość od czoła ściany). SSMS dostarcza dane do Systemu Predykcji Warunków Wydobycia LMCPS (ang. Longwall Mining Conditions Prediction System), w celu prognozowania ryzyka zawału stropu i generowania informacji o koniecznych działaniach naprawczych. Projekty opracowane w ITG KOMAG doskonale wpisują się w aktualne trendy rozwoju systemów mechanizacji i automatyzacji przemysłu, w tym górnictwa.

1. Introduction

Mechatronics includes elements of Mechanics, Electronics, Control and Information Technology and it is used, among others, for designing of state-of-the-art automated and robotized machines and equipment, including industrial robots. According to the definition (approved by the International Federation for the Theory of Machines and Mechanisms), Mechatronics is “a synergic combination of Fine Mechanics, Electronic Control and Systematic Thinking while designing products and production processes” [1, 2].

Products of mechatronics and mechatronic systems should be characterized by multifunctionality, flexibility and a possibility of an easy configuration, as well as by an adaptation ability and operational simplicity. It can be stated explicitly, that in fact this subject-matter has been developed for a dozen or so years by scientists and manufacturers of products working for the mining industry, which will be illustrated with some examples in a further part of this paper. A confirmation of the fact that mechatronics in the mining industry already has an established position, is a requirement of knowledge and education, being one of the professional qualifications indispensable for a person performing activities in the supervision of underground mining operations in the scope of machines and equipment as regards their mechanical part.

KOMAG, with regard to the necessity of increasing the safety of mining crews and improving the efficiency of coal mining, transport and processing, implements a number of research projects aimed at implementing state-of-the-art control and communication systems. Among others, a state-of-the-art, self-organizing and wireless sensor network is being developed. The wireless sensor network can operate in connection with control systems or operate independently. Currently, one system of wireless distributed sensors is introduced in the mining market [3, 4]. Meanwhile, in order to become more competitive, the mining industry has to invest in further solutions of this type, especially in the area of equipment for mine roadways, e.g. belt conveyors for the transport of the extracted coal, with lengths ranging from hundreds of metres to several kilometres. This is a result of fast changes in the configuration of machines resulting from the progress of mining works and activities aimed at automation and autonomy of mineral excavation technologies.

Development of self-organizing, distributed, wireless sensor networks and control systems requires the development of an alternative method of powering their elements by recovering waste energy available in their surroundings, e.g. energy of mechanical vibrations, thermal energy [5, 6], as well as energy of rotary motion or electromagnetic radiation. The development of electronic systems with low power demand and the development of low power radio data transmission standards makes it easier to use wireless sensors [1, 7]. Self-powered sensors are often used in ventilation or air conditioning systems.

Artificial intelligence methods are increasingly used in communication between machines used in mining. They are particularly used for monitoring and diagnostics of subassemblies and component wearing [8, 9, 10, 11] and in machine control systems and mechanisation systems [12, 13]. According to KOMAG's experience, the three hardware and software components of the discussed solutions are of the greatest importance for operational reliability: self-powered sensors, distributed control systems and self-organized communication network binding these components into one system.

2. KOGASTER - distributed control and diagnostics system

Distributed control systems are a class of systems in which the controllers are physically separated over a certain area covering a monitored or controlled object. It is different from a centralized control system in the absence of a structure that clearly focuses control functions in one device. In a distributed control system (DCS), each component, each machine or device is managed by a dedicated controller. A DCS consists of a large number of local controllers, located in different zones of the installation/machine area, which are connected via an efficient communication network. Research and development projects carried out at KOMAG have become the basis for the development of distributed control system modules offered under the name KOGASTER. This system is a good example of an installation covering potentially large areas (up to 1 km in diameter), in which sensors, actuators, control units are located and connected by wired or wireless communication network. In addition, KOGASTER can be implemented in a mining environment. It is designed for use in machines operating in difficult conditions, especially in potentially explosive atmosphere, where the use of explosion-proof automation systems is required. The KOGASTER system has been certified under the ATEX Directive. The system has been designed to ensure a high level of safety (switching off the power supply in case of an explosive atmosphere, as well as in difficult working conditions, in particular due to its improper use and in case of changes in environmental conditions). The components making up the KOGASTER system are classified in the 1st explosion Group. The open structure of the communication protocol enables connecting KOGASTER system elements with elements (transmitters, sensors) from other manufacturers. KOGASTER elements can be used in machines equipped with both intrinsically safe and extrinsically safe circuits.

The KOGASTER system is a distributed system that operates using the CAN bus and CANopen protocol for communication [14, 15]. It is intended primarily to control mining machines and equipment [6, 16, 17, 18, 19]. The implementation of the CAN bus and the CANopen protocol enabled the construction of a system with open architecture. The main characteristics of the KOGASTER control system are as follows:

- distributed structure [20],
- intrinsically safe and redundant CAN bus [21],
- intrinsically safe sensors, input/output systems and control units [22].

2.1. Structure of distributed control system

The distributed control system consists of control modules, I/O, measuring transducers, actuators and digital communication interface, connected to the CAN bus. The advantage of this solution is the possibility of power supply and data transmission in one wire harness. The block diagram of the distributed control structure with the use of a single CAN bus is shown on Figure 1.

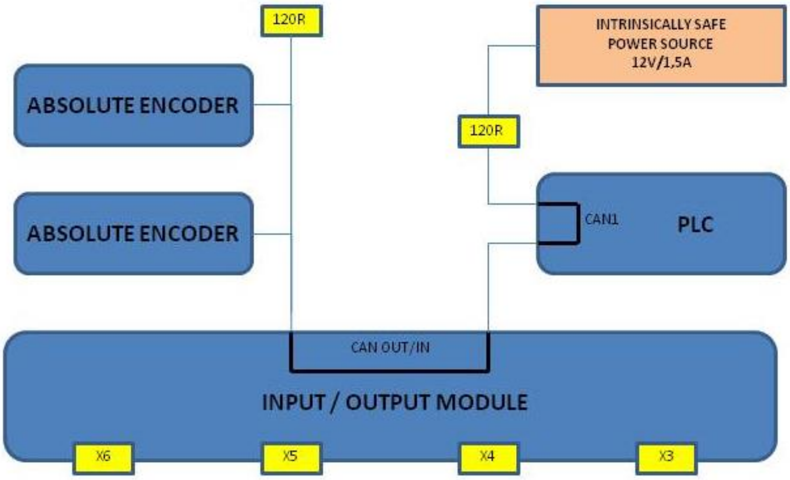

Fig. 1. Block diagram of distributed control system using a single CAN bus [23]

The CAN bus becomes reliable due to the redundancy of the cabling and the doubling of modules and transmitters. This has a negative impact on the unit cost of production, but allows to reduce costs resulting from machine failure. An example of using a redundant system is a battery-driven train equipped with two independent control panels and two drives, shown in Figure 2.

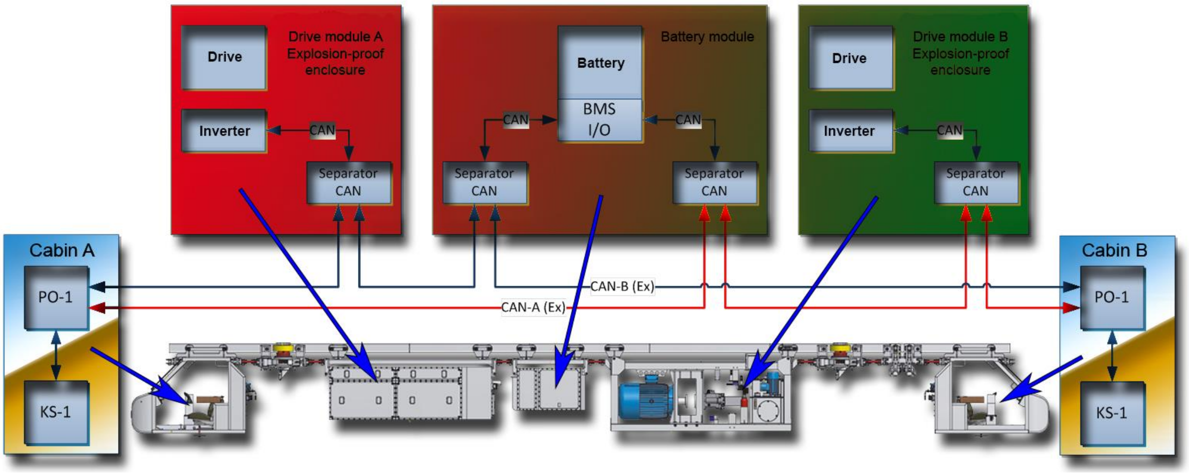

Fig. 2. Block diagram of a train control system with a redundant distributed structure [23]

3. Systems for measuring the operational parameters of roof support

Nowadays, there are systems in manufacturers offers for measuring selected parameters of powered roof support sections. The properties of these systems are strongly diversified, mainly in terms of data transfer and power supply. The analysis of solutions offered on the market indicates that mainly wired and wireless systems for measuring pressure in legs are available. The purpose of measuring the pressure in legs is to determine the load-bearing capacity of the roof support unit, as well as to verify the proper selection of the roof support section to the operating conditions prevailing in the longwall [24]. In the scope of roof support geometry measurements, wire-based systems are available.

At the present, systems of automation of longwall systems does not include monitoring of roof and preventing against danger phenomena associated with roof behaviour, such as roof falls to the longwall face or lack of roof fall behind the shield support. The KOMAG's coordinated PRASSIII project goals are focused on the Shield Support Monitoring System (SSMS), which will enable monitoring of roof condition, by monitoring the parameters of shield support, as well as on development of the Longwall Mining Conditions Prediction System (LMCPS) for a prediction of roof fall hazards and a generation of information about corrective measures [25]. Presented scope of work is realized within the PRASS III (Productivity and Safety of Shield Support) project. The project is realized by international consortium consisting of the following organization: the KOMAG, the Becker Warkop Ltd. Company, the Main Mining Institute (GIG), the Jastrzebska Coal Company Ltd. , the DMT GmbH & Co. KG, the Geocontrol and the University of Exeter.

3.1. The Shield Support Monitoring System (SSMS)

The Shield Support Monitoring System (SSMS) will include geometrical parameters of shield support, hydraulic pressure parameters, tip to face distance and new wireless communication system. The SSMS will enable monitoring and recording roof support operational parameters in real time and it will be the basis for a development of the Longwall Mining Conditions Prediction System (LMCPS). For monitoring geometrical parameters of powered roof support, the SSMS will include a set of sensors enabling a determination of an absolute position of each powered roof support component. All the devices of the SSMS will meet the requirements of the ATEX Directive.

3.2. The Longwall Mining Conditions Prediction System (LMCPS)

It was concluded that by monitoring the behaviour of the both shield support (leg pressures, geometry and tip to face distance) and geotechnical conditions in longwall, warnings can be given for significant improper shield support acting and the formation of roof instabilities tens of minutes in advance. This advance warning allows miners to take preventive action (such as improvement of roof strata stability by injections or improvement the shield support) which can reduce longwall downtime and hazards.

4. Power Supply System of roadheading mining machines

Roadheading machines are commonly used in the Polish coal mining industry, for activities related to proper maintenance of the false floor in the roadway developments. They are self-running machines on a tracked electro-hydraulic drive chassis. During drilling, a hydraulic pump, driven by an electric motor, powered by a drop-down cable is connected to the mine power network. The disadvantage of this solution consist in a limited mobility and an exposure of the cable to mechanical damages, so research work was undertaken by the KOMAG.

In order to increase machine operational availability, it was planned to power the machine with electricity through the so-called electric hybrids. It is a system based on wired network power from the mine network and additionally on independent power supply from cell batteries. The machine will work on battery power. When the battery has been discharged, it will be possible to supply the machine from the mine network, thus continuing the work while simultaneously charging the battery cells. After the battery has been charged, the machine will be reenergized only from the internal source. The current regulations on the use of cells in underground explosive mines require only serial connections, and thus the possibility of increasing the voltage while maintaining the capacity of a single cell. Therefore, cells with a capacity of 100Ah in the number of 224 units connected in series were selected. The battery will consist of fourteen modules containing 16 cells in each module. Figure 3 shows an assembly of a single set of cells (modules) in the protective cassette.

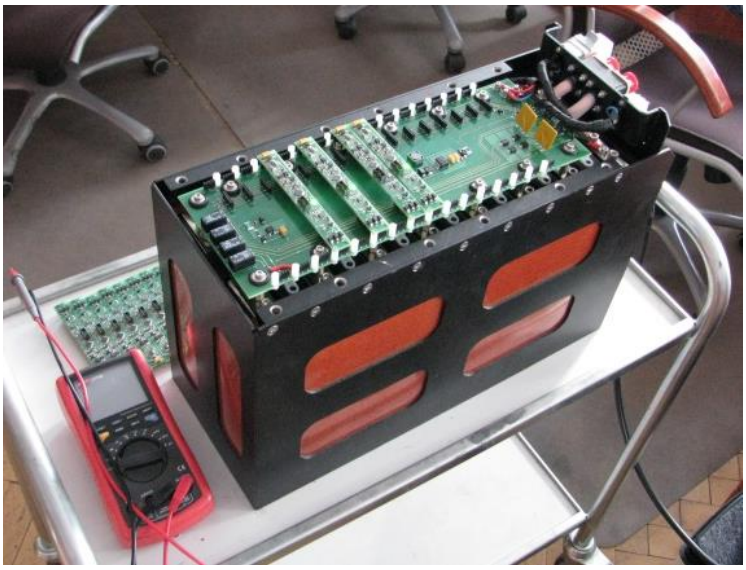

Fig. 3. A single set of cells in the protective cassette [26]

The main element of the electrical equipment of the new power supply and control system will be a fully controllable converter fulfilling the functions of the inverter and power supply for the battery. The auxiliary AC and DC auxiliary voltages necessary for operating the machine and supplying the protection are to be obtained from 500 V. Due to the higher harmonics occurring during the transformation of the battery voltage from the battery by the inverter, it will be necessary to use appropriate filters. The converter will power the dSLg250M4-EP type motor, it is a three-phase, asynchronous electric motor, adapted to work in potentially explosive atmospheres. This engine is widely used in mining, also in extant drive systems of mining tailings. The inverter and loader work on a common power line for the hydraulic pump drive motor. After discharging the battery, through the appropriate switching sequence, after connecting the power cable, the system allows battery charging and direct powering of the drive motor from the electric mining sieve. Thanks to this solution, the functionality of the machine has been increased compared to the solutions used so far. An additional functionality in which the new power supply and control system was designed is a wireless control and communication system. The existing solutions of mining machines of small mechanization are controlled locally by means of a manipulator located in the operator's panel. The proposed wireless control system will be based on the system developed in the KOMAG. This system is adapted to work in mining excavations where there is a danger of explosion of methane levels "a", "b" and "c" and the explosion hazards of dust class A and B. The system consists of a receiver and a pilot. The receiver, which is a part of the system, is a microprocessor device used to receive control signals sent with a wireless remote control. On the basis of sent setpoints, the receiver module generates signals controlling the machine's automation. After turning on the receiver's power supply, the microprocessor system starts, which enters the state of waiting for connection with the remote control. After starting the remote control, the receiver establishes a connection with it. Properly programmed microprocessor controls the relays according to the data sent from the remote control, which is adapted to the needs of a particular device - the number, designation and selection of the location of the buttons depend on the purpose of the system. The control signals are sent in the form of serial data, and the transmitted block of data contains information about the operating status of the keyboard's control buttons.

During the tests, a correct operation of the battery charging and discharging module as well as the control and safety system was checked. In the result of these tests, no irregularities were found. The current intensity when charging cell batteries was about 30A, this allows to charge the battery in about 3 hours, which is the fulfilment of the technical and technological assumptions. The combined control and safety system guarantees that every irregularity, created in the power module, is detected and blocked by the developed security system. When the power module did not confirm a connection of the mobile machine's electrical motor during testing, only the output voltage and communication of the power electronic converter were verified during the tests.

5. Intelligent algorithms for routing sensory networks

Sensory networks must ensure a reliable transmission of measurement data in order to detect fault conditions that pose a direct threat to the progress of the mining operation and often also to the health and safety of employees.

Working conditions in mines make it difficult to service machinery and equipment. The installation of a new measuring system, a replacement of a sensor, and maintenance actions should be simplified by the type of machine sensors used. The following elements become important for operational reasons:

- an easy assembly and replacement of the sensor (no need to use wires makes it easier to install and adapt to the structure of the machine or the environment in which it works); the sensors should be powered by batteries or by energy recovery, with the sensory data transmitted via radio signal,
- sensors should be replaced without the need to reconfigure the network in which they are located,
- sensors should transmit information among themselves so that, due to interference from metal elements, it is not necessary to transmit information directly to the access point.

In order to meet these requirements, it is necessary to implement appropriate routing algorithms in sensory networks:

- Proactive algorithms - store routes between individual network nodes in the so-called routing tables; these routes are cyclically refreshed so that the stored data are consistent with the current state of the network (the so-called maintenance of paths takes place regardless of whether there is traffic to individual nodes of the network),
- Reactive Algorithms - these algorithms search for a route when necessary, at the time of sending a packet,
- Hybrid algorithms - in these algorithms, the network is divided into smaller parts. Only separated parts of the network are saved.

5.1. Routing algorithm for conveyer sensory network

For eight years KOMAG has been developing the concept of a self-organized communication structure protocol called SSKIR [21], which is based on the implementation of hive intelligence [10].

Based on the behavior of individuals in animal swarms, a number of principles were developed [21, 27] and proposed to create a system of communication in the sensory network (Fig. 4). Each data frame transmitted by the Measure Transmission Unit (MTU) is marked with the transmission quality factor Wp defining the transmission priority related to the efficiency of data transmission to main transmitting stations. This factor may take a value according to one of the connections or route metrics.

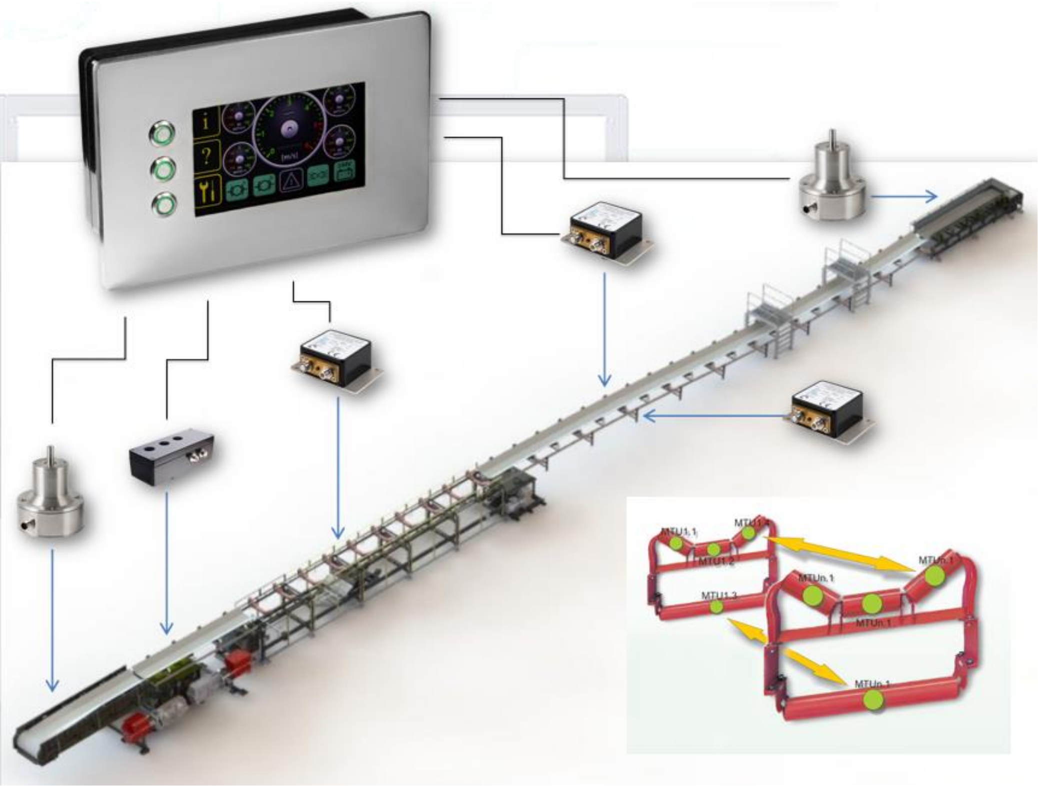

Fig. 4. Sensory network of belt manipulator rollers [27].

As mentioned above, the W_P coefficient can take a value that conforms to one of connections or path metrics; therefore, transmission speed and the number of hops of transmitted frames containing the following measurement data is based on data propagation times:

- Expected Transmission Count (ETX) is a metric that is widely used in mesh networks; ETX is the metric specifying the number of expected transmissions, which is indispensable when sending data to the next node without errors; the number varies from 1 to infinity.
- Expected Transmission Time (ETT) is an extension of ETX metrics, since it takes into consideration the difference in the speed of data transmission. The relationship between ETT and ETX metrics can be expressed as follows:

$$ETT_l = ETX_l \frac{s}{b_1} \tag{1}$$

where:

b_l - a speed of transmission of information in connection l,
s - a size of transmitted package.

- Hop count is the most often used routing metric in the existing routing protocols, such as DSR (Dynamic Source Routing), AODV (Ad Hoc On-Demand Distance Vector), or DSDV (Destination-Sequenced Distance Vector).

- Weighted Cumulative ETT (WCETT) is a metric that includes both the quality of a connection (losses, throughput) and the number of hops; thus, we can reach a compromise between delay and throughput.

$$WCETT(p) = 1 - \beta \cdot \sum_{l \in p} ETT_l + \beta \cdot \max_{1 \le j \le k} X_j \tag{2}$$

where:

β - a set parameter from the range $0 \le \beta \le 1$ (higher values of β give priority to paths using many channels and its lower values give priority to shorter paths),

$\max_{1 \le j \le k} X_j$ - counts the maximal time of appearance of the same channel in a given path.

- MIC is metric that improves the operation of WCETT by solving its isotonicity and inability of detecting the collisions; MIC metrics of p path can be defined as follows:

$$MIC(p) = \frac{1}{N \cdot \min(ETT)} \sum_{linkij \in p} IRU_{ij} \sum_{nodei \in p} CSC_i \tag{3}$$

where:

N - a number of all nodes in the network,

min(ETT) - the lowest *ETT* in the network and it can be determined on the basis of the lowest speed of data transmission in radio charts.

The transmission factors are calculated and stored in the network nodes. There is no need to create a master routing map describing the structure of the entire network. Application of specified rules causes that a group of MTU units creating a transmission path automatically creates a structure of reliable transmission routes, omitting units which have failed. Data frame in SSKIR protocol is defined by four additional values:

- its own unique MTU identification number,
- *X* and *Y* coordinates defining the occupied position in the solution space of the communication path structure,
- the priority factor in the communication path of which the frame is an element,
- the baud rate for the *X* and *Y* dimensions, i.e. *vX* and *vY*.

The neighbours of frames with the number of a given MTU are called other frames that are in the MTU transmission range, i.e. those that are in a sufficiently short distance d and simultaneously in the field of view, defined by the value of virtual angle *r*. In order to check whether a given frame *e* of coordinates *e.X* and *e.Y* respectively, is a neighbour of MTU *b* of coordinates *b.X* and *b.Y*, it is necessary to check first whether the element is in a sufficiently short distance. If the condition is not met, then the next rules are not checked, because a given frame from the MTU *e* is certainly not a neighbour of frames from the MTU *b*. If the condition is met, it is checked if the frame is in the virtual viewing angle *r* by determining the angle r_1 under which the frame moves virtually:

$$r_1 = \arctan\left(\frac{b.vY}{b.vX}\right) \tag{4}$$

and the virtual angle r_2 of the segment connecting the MTU *b* frame with the MTU *e* frame assuming that $b.vX \neq 0$ and $e.X - b.X \neq 0$. Then the absolute value of the angle difference is calculated and the inequality checked. If the condition is met, then the frames come from neighbouring MTU. Next, the first rule is applied, and each frame adjusts its path to frames from neighbouring MTU. One must calculate the average speed v_{avg} of all frames from the neighbouring MTU (separately for the *vX* and *vY* components) and then modify the frame transmission speed, taking into account the path priority factor, the current speed, and the calculated average.

To apply the second rule, the average number of frame jumps in the d_{avg} transmission path should be calculated in relation to frames from neighbouring MTU, and then the frame transmission speed should be modified in relation to neighbouring MTU.

The third rule shows that, when a frame in a path with a lower priority coefficient tries to carry out the transmission, competing with a frame with a higher priority, it should avoid it by modifying its speed. Formula (5) also use the triangular similarity claim. Let *b* be a lower priority frame competing with a frame from the neighbouring MTU, with a higher priority *e*. In regard to the above rule, the following formula should be applied:

$$\begin{aligned} d &= \sqrt{(e.X - b.X)^2 + (e.Y - b.Y)} \\ b.vX &= b.vX + \left(\frac{\left(e.X - b.X\right) \cdot d_{\min}}{d} - \left(e.X - b.X\right) \right) \\ b.vY &= b.vY + \left(\frac{\left(e.Y - b.Y\right) \cdot d_{\min}}{d} - \left(e.Y - b.Y\right) \right) \end{aligned} \tag{5}$$

where:

d_{min} - a preset minimum number of jumps in the transmission path, which should not be exceeded by the transmitted frame.

The last two rules are introduced to the system by modifying the fourth rule based on the dependencies [21]. It should be noted that each frame can move with a certain maximum speed imposed by the physical system. In simulations, this speed should be limited and the following entered:

- limitations resulting from the presence of MTU in the emergency or start-up state (elements that frames should avoid creating transmission paths),
- attractors in the form of main receiving and transmitting stations.

6. Summary

Adaptive control systems are used more and more widely in industrial practice. Industrial Internet of Things (IIoT) and direct communication of machines (M2M, Machine to Machine) significantly impact technical and management structures in companies implementing Industry 4.0 solutions. KOMAG develops these solutions by designing adaptive, self-organizing communication systems based on mesh topology. The method of system self-organization is based on a swarm algorithm. It enables implementation of state-of-the-art and effective routing technology in networks with mesh topology, especially in diagnostic systems. Networks equipped with MTU nodes can be treated as components of measurement swarms. This is particularly important for the safety of underground mine operations due to the reliability of transmission in mesh networks.

The practical use of low-power waste energy recovery has become possible thanks to the use of low energy consumption sensory and communication systems, which enable the management of energy coming from vibrations, heat, light and supply it to entire sensory and communication networks.

KOMAG has strongly marked its position in the area of distributed explosion-proof control systems. The KOGASTER control system based on the CAN bus and CANopen protocol has been designed mainly for the control of mobile machines, and the use of intrinsically safe components in the KOGASTER system enables its implementation in the control of machines and equipment operating in areas with methane and coal dust explosion hazard.

References

[1] Sztucki T. Marketing przedsiębiorcy i menedżera. Agencja Wydawnicza Placet, Warszawa 2000 (in Polish)

[2] Jasiulek D., Malec M., Polnik B., Stankiewicz K., Trenczek S.: State-of-the-art mechatronic systems for mining developed in Poland. Materiały na konferencję: APCOM 2019, Application of Computers and

Operations Research in the Mineral Industry, 39th International Conference, Mining Goes Digital, Wrocław, Poland, 4-6 June 2019 s.686-694, ISBN 978-0-367-33604-2.

[3] Tanenbaum A.S., Stehen M.V.: Systemy rozproszone. Zasady i paradygmaty. Klasyka informatyki. Warszawa: WN-T, 2006 (in Polish).

[4] Wischke M., Masur M., Kröner M., Woias P.: Vibration harvesting in traffic tunnels to power wireless sensor nodes. Smart Materials and Structures, 2011, 20(8), 085014.

[5] Stankiewicz K., Woszczyński M.: Metody odzyskiwania i przetwarzania energii cieplnej. Maszyny Górnicze, 2010, 1, pp. 39–46 (in Polish).

[6] Woszczyński M., Świder J.: Use of the System for Energy Recuperation and Control in Diesel Machines. Machine Dynamics Research, 2014, 38(1), pp. 73–79.

[7] Sudevalayam S., Kulkarni P.: Energy Harvesting Sensor Nodes: Survey and Implications. IEEE Communications Surveys & Tutorials, 2011, 13(3), pp. 443–461.

[8] Boukerche A.: Algorithms and Protocols for Wireless and Mobile Ad Hoc Networks. Ottawa: Wiley,2009.

[9] Jasiulek D., Stankiewicz K., Jagoda J.: Możliwości zastosowania czujników samozasilających się przeznaczonych do pracy w podziemiach kopalń. Mechanizacja i Automatyzacja Górnictwa, 2013, 8(519), pp. 73–80 (in Polish)

[10] Reynolds C.W.: Flocks, Herds, and Schools: A Distributed Behavioral Model. Anaheim: SIGGRAPH, 1987.

[11] Vullers R.J.M., van Schaijk R., Doms I., Van Hoof C., Mertens R.: Micropower energy harvesting. Solid-State Electronics, 2009, 53 pp. 684–693

[12] Cunefare K.A., Skow E.A., Erturk A., Savor J., Verma N., Cacan M.R.: Energy harvesting from hydraulic pressure fluctuations. Smart Materials and Structures, 2013, 22(2), pp. 729–738.

[13] Latos M., Stankiewicz K.: Studies on the effectiveness of noise protection for an enclosed industrial area using global active noise reduction systems. Journal of Low Frequency Noise, Vibration and Active Control, 2015, 34(1), pp. 9–19.

[14] Gong T., Tuson A.L., Particle swarm optimization for quadratic assignment problems – a formal analysis approach. International Journal of Computational Intelligence Research, 2008, 4, pp. 177–185.

[15] Gładysiewicz L., Król R., Bukowski J.: Tests of conveyor resistance to motion. Eksploatacja i Niezawodność – Maintenance and Reliability, 2011, 3, pp. 17–25.

[16] Bartoszek S., Jagoda J., Jura J., Latos M.: Systemy wbudowane w zespołach sterowania, diagnostyki oraz wizualizacji dla górnictwa. In: Klich A., Kozieł A. (eds.): Innowacyjne techniki i technologie dla górnictwa Bezpieczeństwo – Efektywność – Niezawodność. KOMTECH 2014. Gliwice: Instytut Techniki Górniczej KOMAG, 2014, pp. 207–218 (in Polish).

[17] Mohapatra P., Krishnamurthy S.V.: Ad Hoc networks (Technologies and Protocols). Springer, 2005

[18] Radkowski S., Lubikowski K., Piątak A.: Vibration Energy Harvesting in the Transportation System: a Review. Diagnostyka – Applied Structural Health, Usage and Condition Monitoring, 2012, 4(64), pp. 39–44

[19] Bartoszek S., Jagoda J., Jura J.: System diagnostyczny ładowarki bocznie wysypującej bazujący na iskrobezpiecznej magistrali CAN. Szybkobieżne Pojazdy Gąsienicowe (32) nr 1, Ośrodek Badawczo – Rozwojowy Urządzeń Mechanicznych OBRUM sp. z o.o., Gliwice 2013

[20] Zhu D., Beeby S.P., Tudor M. J., Harris N. R.: A credit card sized self-powered smart sensor node. Sensors and Actuators A: Physical. Volume 169, Issue 2, October 2011, Pages 317–325

[21] Stankiewicz K. Self-organization of network structure based on swarm algorithms. Problemy Eksploatacji – Maintenance Problems 2014; 2: 5-14.

[22] Sazonov E., Li H., Curry D., Pillay P.: Self-Powered Sensors for Monitoring of Highway Bridges. IEEE Sensors Journal, Vol. 9, NO. 11, November 2009

[23] Bartoszek S., Jagoda J., Jura J., Latos M.: Systemy wbudowane w zespołach sterowania, diagnostyki oraz wizualizacji dla górnictwa. Monografia KOMTECH 2014, Instytut Techniki Górniczej KOMAG, Gliwice

2014, ISBN 978-83-60708-83-5

[24] Płonka M., Rajwa S., Lubosik Z. Ocena pracy obudowy zmechanizowanej na podstawie danych z monitoringu ciśnienia i postępu sekcji. Przegląd Górniczy nr 4/2017. 25-33

[25] Jasiulek, D., Bartoszek, S., Perutka, K., Korshunov, A., Jagoda, J., Plonka, M.: Shield Support Monitoring System - operation during the support setting. ACTA MONTANISTICA SLOVACA. Volume: 24. Issue: 4/2019. Pages: 391-401.

[26] Polnik B.: „An Innovative Power Supply System Dedicate for Roadheading Mining Machines" - ECS Transactions, 87 (1) 349-362 (2018), str. 349.

[27] Stankiewicz K.: Smart mining communication systems. Materiały na konferencję: Future Engineering 2019, 5th International Scientific and Business Conference, Ołtarzew, Poland, 29-30 May 2019 s. 120-131, (DEStech Transactions on Computer Science and Engineering 2019 FE) ISSN 2475-8841; ISBN 978-1-60595-632-9.