Abstract

J. Jagoda: Development and validation of a sensory network routing algorithm, with the application of swarm intelligence

The scientific objective of the thesis was to perform and validate a sensory network routing algorithm using swarm intelligence working in the monitoring of powered roof support sections. The thesis adopted the following thesis:

> *The use of sensory network routing algorithms (working on the basis of swarm intelligence) implemented in methane and/or coal dust hazardous areas will ensure adequate organisation of information transmission, while increasing the required operational reliability, flexible configuration and required level of operational safety.*

The utilitarian objective of the dissertation was also defined, which is to develop a solution to support the automation of the longwall driving process and a system for the prediction of hazards (such as rock bursts).

As part of the literature analysis, the operating environment of the designed routing algorithm was defined in the form of monitoring the operating parameters of shield suport section. Shield support sections perform the function of protecting equipment and crew during the longwall mining process. The precise positioning of the section in the excavation is crucial for the continuity and safety of the mining process. The monitoring of section parameters, such as the value of oil pressure in hydraulic stands, the current geometry of the section (i.e. the location of selected elements of the section in relation to the excavation), the distance from the longwall face, will make it possible to identify potential structural problems and to adapt the adopted exploitation and protection methods on the basis of the collected data (an analytical tool for predicting such hazards as rock bursts, caving and collapses). In systems monitoring the described parameters of hydraulic racks, it is necessary to develop wireless interfaces for the monitoring sensors, due to the frequent failure of the cables of the solutions currently in use. In such extensive networks of mine workings, it is important to construct an effective data transmission organisation aimed at

ensuring operational reliability, flexible configuration and operational safety. Operational reliability means being confident that the data recorded by the sensors will reach the dispatch point. The reduction of sensor failure rates should therefore be influenced and the process of identification and replacement should be accelerated in the event of sensor failure. A flexible configuration should be provided due to the increased efficiency of service processes and network operating conditions in the planned solution. The implementation of the prototype network should be easy to implement, scalable, secure and require low implementation and commissioning time. Most emerging sensor networks installed in mining equipment and machinery have wireless data transmission interfaces and the sensors themselves are battery powered. Sensors, in terms of design and function, must meet the requirements to be able to operate in methane and/or coal dust hazardous areas as defined by the European ATEX (Atmosphères Explosibles) directive. It is not uncommon that ensuring safety through proper electrical design of equipment involves higher energy consumption, resulting in shorter battery life. There is therefore a need to optimise energy consumption.

The dissertation also analysed simulation tests of currently used sensory network routing algorithms. As a result of the review, it was found that the use of protocols based on swarm intelligence has a positive effect on stabilising and increasing throughput in sensory networks compared to typical reactive and proactive type routing algorithms. It was also concluded that implementations of selected types of algorithms in hardware solutions are necessary, as well as performing validation of simulation results and prototyped solutions.

The state of the art research also allowed the specification of detailed criteria for the selection of the most favourable route for data packets transmitted in sensor networks. In the process of defining the criteria, the initial assumptions for the solution being developed as part of this dissertation were taken into account, with the analysis performed in two areas:

- algorithms and networks - throughput, packet arrival time, energy savings, certainty of data delivery to the destination,
- hardware - in establishing the criteria, consideration was given to available sensor solutions and additional system components, which must meet the aforementioned

algorithmic and networking requirements and have an adequate level of reliability and dependability for operation in adverse environments (energy efficiency and ATEX compliance).

In the next step, a method for implementing the algorithm into a model and prototype of the sensory network was developed. The implementation process of the algorithm is also described, together with details of the implementation in the software stack of the individual hardware modules of the network nodes.

This paper discusses the prototyping process of a routing algorithm validation environment in a network of three nodes and a network environment containing up to 30 nodes. A radio module that acts as a network node (Nordic Semiconductor's nRF52 radio module) was specified. For all hardware components of the validation environment, software was developed to enable the implementation and testing of the algorithm, together with the measurement of specific parameters of the sensory network operation. Proprietary GMESH software was created to display the content of diagnostic packets sent from the sensor networks, visualise the data transmission path and present the time dependencies of individual sensor network evaluation criteria in graphs.

Validation tests of algorithms based on swarm intelligence (selected at the simulation analysis stage) for the sensory network model were carried out. The tests concluded that:

- the values of the criteria of the implemented algorithms differed slightly between each other and in comparison with the results obtained using the base (reactive) algorithm of the Fruity Mesh network, In the case of the arrival time of individual data packets, the values were a few milliseconds, while in the case of the arrival time of transmitted data packets, the values were a few tens of milliseconds. Differences in the recorded throughput of transmitted data were within a few tenths of a kB/s,
- in the further implementation, the bee algorithm was rejected due to the longest execution times of the procedure for selecting the optimal path for the transmission of the data packet, which tend to increase exponentially in the case of extended networks,

- the process of implementing the algorithms in the network model has made it possible to note that in the case of the ant and bee algorithm, there is also a risk of looping in the network (the selection of the best partner of a NODE node may result in the information not reaching the destination node). In the case of the ant algorithm, each NODE node has to continuously calculate and update route probability values based on pheromone traces, which increases the computational load on the nodes (especially in large networks). Similarly, for the bee algorithm, each NODE-type node has to process information from other nodes (i.e. bees) and calculate the attractiveness of different routes, which also puts a strain on the computational resources of a single node. In both algorithms, nodes need to store information about multiple routes, pheromones (ACO) or food sources (BEE), which requires large amounts of available memory. Simple microcontrollers, in particular the battery-powered units used in NODE nodes, are characterised by limited memory resources posing a significant problem with a large number of nodes and complex calculations. Therefore, an algorithm based on particle swarm optimisation using elements of the ant algorithm is proposed for further research. The conducted research on the model of a sensory network provides a basis for testing a prototype network consisting of at least 30 nodes,
- in all the objective functions of the implemented algorithms, weights were introduced, which influence the optimisation of the data transmission process in the network according to the relevant criterion. Due to the introduced assumption, in the next stages of the work (during the realisation of the tests of the sensory network prototype), the influence of the choice of weights, on the results of the individual criteria, should be analysed,
- as a result of the research, a test bench configuration concept was also proposed, which made it possible to test a network composed of a larger number of nodes.

The developed algorithm was then implemented into a prototype sensory network and tests were carried out according to the adopted criteria. It was found that as the number of nodes increased, there was a decrease in throughput and an increase in packet delivery time (with throughput stabilizing in the range of 1.6-3.1 kB/s in a network with 10, 20 and 30 nodes). Testing of the network reconfiguration process showed that network adaptation times were in the range of 10-20 seconds. The correct operation of the network with mobile nodes was also confirmed. The current measurement did not show significant differences after applying the proposed algorithm, but it was evident that the PDR was kept high to prevent the network nodes from discharging quickly (extending the operation time of the nodes with battery power).

In order to make inferences, a comprehensive analysis of the recorded measurement data was carried out. For this purpose, statistical analyses of the recorded values for the individual criteria were performed. As a result of the analyses, it was found that the algorithm with swarm intelligence (SI) significantly improves the values for packet arrival time, throughput and packet delivery ratio (PDR) compared to the traditional algorithm. The algorithm with AI allows packet arrival time to be stabilized at around 150 ms (with 25 or more nodes), throughput to be increased to 3 kB/s (in a 30-node network) and PDR to be maintained above 94%. The results of the Mann-Whitney U test confirmed statistically significant differences in favour of the algorithm with SI, demonstrating its superiority in managing the sensory network.

The work also included an analysis of the technology for making sensor network node enclosures in explosive atmospheres. As a result of the analyses, it was found that the choice of technological process for making the enclosure depends on the size of the production series and meeting the requirements of the ATEX directive. In the case in question, it is assumed that single prototypes and approximately 100 units per year will be manufactured. At the assumed production scale, the use of injection moulding technology is uneconomic. In the case of 3D printing technology and CNC machining, there are materials available on the market which meet the requirements for antistaticity. However, it has been shown that the materials do not have a certificate of conformity with standards harmonised with the ATEX directive, and manufacturers declare compliance with the requirements for surface resistance (which requires confirmation by additional measurements after manufacture of the housing). Silicone mould casting technology requires the application of an additional anti-electrostatic coating. Prototype enclosures are most cost-effective with 3D printing technology due to the flexibility of the design. On the other hand, the manufacture of enclosures in small series (up to 100 units) is most economically justified using silicone moulds.

Calculations and analyses of the electrical circuits of the network nodes were also carried out to check their compliance with the requirements of the ATEX directive. The analyses carried out confirmed that the designed NODE and SINK nodes meet the requirements of standards harmonized with the ATEX directive (including PN-EN 60079-0 and PN-EN 60079-11). Detailed analyses of the rating and derating parameters of electronic components were also performed, confirming their compliance with intrinsic safety requirements.

The conclusions indicate the need for further work to develop the routing algorithm and verify its performance in-situ. Due to the development of Industry 5.0, as well as the idea of IIoT in the mining industry, the number of diagnostic elements working in sensory networks is increasing. The research conducted has shown the feasibility of using algorithms based on swarm intelligence to manage data transmission in sensor networks operating in methane and/or coal dust hazardous areas. However, further research is needed to extend the algorithm to operate in networks consisting of thousands of nodes.