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# New mechanisation and automation of longwall and drivage equipment (NEMAEQ)

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Research Fund for Coal and Steel Unit

*Contact: RFCS publications*
*Address: European Commission, CDMA 0/178, 1049 Bruxelles/Brussel, BELGIQUE/BELGIË*

*Fax +32 229-65987; e-mail: rtd-steel-coal@ec.europa.eu*

European Commission

# Research Fund for Coal and Steel

# New mechanisation and automation of longwall and drivage equipment (NEMAEQ)


Dr. J. Czwalinna (1), J. Kubik (2), Dr. D. N. Bigby, Dr. L. Kent (3),
S. Bennett, C. Talbot (4), P. Wiszniowski (5), A. Piecha, D. Jasiulek (6), C. Sauer (7),
A. Rodriguez, F. J. Espada Moreno (8), C. Müller (9)

(1) **Evonik Degussa —** Paul Baumann Straße 1, 45764 Marl, GERMANY
(2) **Deutsche Steinkohle AG (DSK, now RAG) —** Shamrockring 1, 44623 Herne, GERMANY
(3) **Rock Mechanics Technology Ltd (RMT, now Golder RMT Ltd) —** Bretby Business Park, Ashby Road, Burton upon Trent, DE15 0QD, UNITED KINGDOM
(4) **Mines Rescue Service Ltd (MRSL) —** Leeming Lane South, Mansfield Woodhouse, Mansfield, NG19 9AQ, UNITED KINGDOM
(5) **Centrum Elektryfikacji i Automatyzacji Gornictwa (now Institute of Innovative Technologies (EMAG)) —** Leopolda 31, 40-189, Katowice, POLAND
(6) **Centrum Mechanizacji Górnictwa (now Institute of Mining Technology (KOMAG)) —** Pszczynska 37, 44-101 Gliwice, POLAND
(7) **Technische Universität Clausthal (UoC) —** Erzstraße 20, 38678 Clausthal-Zellerfeld, GERMANY
(8) **Asociación para la Investigación y el Desarrollo Industrial de los Recursos Naturales (Aitemin) —** Margarita Salas, 14, 28918 Madrid, SPAIN
(9) **Embigence GmbH —** Goethestraße 52, 49549 Ladbergen, GERMANY



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# 2 FINAL SUMMARY

This chapter addresses the most significant aspects on a task by task basis addressing project objectives, results obtained and their usefulness, plus possible applications and patents.

## 2.1 AUTOMATION OF LONGWALL EQUIPMENT (WP1)

This work package aimed at full automation of the shearer loader operations, i.e. steering of support arm and cowl, control of machine speed and adjustment to match the shield support control. Hence a series of technical conditions had to be met in order to ensure automatic face navigation, in particular

- Identification of the coal- rock- interface,
- Avoidance of collisions,
- Load dependent regulation of shearer loader speed and the locating of the winning equipment.

In order to allow automation suggestions were developed for face end systems.

### 2.1.1 Determination or establishment of the parameters to be observed and the state of the art and knowledge from previous projects

A review on previous project results and state of the art technologies let to the following results:

For coal/rock interface detection investigations and tests revealed Impact Sound and Infrared Measuring as most appropriate amongst 10 candidate methods. According to positive experience from an earlier monorail application an Ultra Wideband Radar was taken into account first for obstacle detection in the face conveyor and of protruding shield canopies. Laser scanners and ultrasonic sensors had to be dropped.

For shearer loader location wireless sensor network technology was taken into consideration as well as synchronisation switches at the shearer loader and magnets at the conveyors end. For Load dependant Shearer Loader regulation a concept was designed for the cooperation among the shearer and the conveyor control subsystems. Experience with embedded systems technologies mining applications as well as software and algorithms suitable for the targeted applications were assessed to identify appropriate and secure technologies for the integration of the IT systems on the shearer into the mine's corporate networking infrastructure.

### 2.1.2 Recognition of coal/surrounding rock interface, collision avoidance, load-dependent speed regulation and shearer loader location

***Coal/rock interface detection***

Raw data recorded during underground tests of first IR sensors revealed structure characteristics which confirmed their applicability. The tests also affirmed that two infrared sensors are necessary to cover the whole seam thickness – one for the middle and one for the upper part of the seam whereas the boundary layer has to be detected by impact sound sensors due to broken coal and rock on the ground averting an IR measurement.

Based on underground raw test data algorithms for longwall image generation and boundary layer detection and a robust image processing process were developed. For the interpretation of the infrared images a special picture editing software was used which scans the pictures in chronological sequence for common pixels. The infrared picture data is correlated with the shearer loader position and saved. Automatic and distance- dependent cropping of the IR images allows to stitch the individual images together. Stair-stepping, fisheye effects and errors are largely eliminated. Additionally a tool was developed assisting the operator to take over and to perform the coal interface detection under poor geological conditions. It provides a visualization of the IR-face images filed and can be used amongst other things for the calibration of the automatic.

All components of the IR camera are protected in a sensor box. A germanium (Ge) window protects the lens which in turn is protected against stone chipping by a grill. An impulse water spray system cleans the Ge window. The reason for chemical corrosion on the window could not be fully ascertained. Efforts to protect the germanium window by coatings did not prove. Consequently the window has to be replaced periodically.

Impact sound sensors proved for the detection of the interface between the seam and the floor as long as the difference in cutting resistance between coal and rock is sufficient. IR sensors don't work here as this area is normally covered by cut coal.

***Collision avoidance***
Synchronization switches at the shearer and magnets at the conveyor proved for collision avoidance at face ends. The rotation of the shearer driving gear is detected in order to meter the distance from the magnets as reference points. Despite the given flexibility of the conveyor pans the shearer position can be ascertained with a precision of +/-1cm through compensating software. The system was invented successfully in various mines meanwhile.

A 24-GHz ultra wideband radar sensor which had proven its applicability for monorail automation in roadways had to be dropped for obstacle detection in the longwall due to lack of resolution. Amongst various types tested a 77GHz dual-range radar sensor turned out to be applicable best. The sensor performs a rough scan for conveyor load evaluation and a precise scan to detect imminent collisions with shield cantilevers. The radar outputs the targets in distance, angle and intensity values. An additional video camera with LED headlights improves the overview in the surface control centre over the face situation in front of the automatically operated shearer.
Design and positioning of the radar housing have to consider attenuation, explosion protection, multipath propagation and maximum dimensions. The case is mounted at a fixed component close to the front. It may neither impede the field of view of the radar nor affect the floodlight on the protective motor housing.

The distorting effect of changing radar vision range and its permanently changing height is compensated through the course of the face gradient recorded on the previous cut. This approach, however, only identifies the gradient between the shearer loader shoes rather than the real course of the gradient. A more precise compensation requiring inertial navigation could not be tested during the project.

***Location of the shearer at the face***
Despite promising tests in laboratory and in an anechoic chamber wireless sensor technology had to be dropped for shearer location as the average accuracy was degraded down to 3m underground, especially since the system used for shearer location at face ends can be applied here, too. The technology can be exploited however in two other RFCS applications with lower accuracy needs.

***Load dependant regulation***
Conveyor overload can be avoided through a load-dependent regulation of the shearer loader speed. This requires data cooperation among the shearer and the conveyor control. Software for controlling and communication between conveyor and shearer loader was developed. The conveyor speed is permanently transferred and the load value is converted in the shearer loader control system to a reduction factor for the speed of the shearer loader. During operation, the speed of the shearer loader is automatically reduced according to the conveyor load if necessary. If a defined overload limit is exceeded, the shearer loader is stopped. This overload protection system has been invented in various longwalls.

***IT level computing infrastructure***
For the integration of the complex sensing technologies the existing control systems of the shearer loader had to be extended by an IT level computing infrastructure incorporating a network of several computers, a machine server and web technologies on the machine. To assure a reliable communication between the shearer and the mine's central IT infrastructure, the machine server functions were extended with special networking capabilities providing multi redundant links: using Wireless LAN, Fiber optic and PowerLine simultaneously or selectively. In this way communication interruptions can be avoided**.**

An embedded machine server was developed as a supplement to the existing real time control systems. Software functionality was integrated to act as a web server for machine information. For network security reasons the machine network functions are separated from the IT level machine control through a network gateway on the shearer enabling the machine server to concentrate on application functions while the separate gateway assures the secure external mine network communication. Meanwhile, this technology is used on longwall shearers and also in other coal mining machinery.

### 2.1.3 Alternative face end support systems and automatic pushing devices

An international review led to the conclusion that face end technologies used elsewhere in the world are not applicable for automation in Germany due to different technologies and geology. That is why further work focused on concepts for easy to handle lining, novel props and a novel face end shield.

A semi circular lightweight steel or fibre-reinforced synthetic U- profile is proposed serving as a casing to be filled with concrete or synthetic material. Sliceable side sections make disassembling dispensable. To replace canopy bars and wooden or hydraulic props an easy to handle and easy to transport 2-component foam filled prop is proposed as face end support and its basic applicability tested. The chemicals forming the foam however, did not pass the obligatory filter self-rescuer test. A face end shield with crawler tracks is proposed to minimize the trample effect. Preliminary calculations reveal the feasibility. A direct exploitation of the technologies considered did not take place.

## 2.2 OPTIMISATION OF THE CUTTING AND LOADING PROCESS FOR COAL SHEARERS, CONTINUOUS MINERS AND AXIAL AND TRANSVERSE ROADHEADERS (WP2)

The objective of this work package was to improve the efficiency of cutting drums of coal shearers, continuous miners and axial and transverse roadheaders. This was to be done by:

(1) the development of numerical models to simulate the process of mechanical rock cutting to:
   - simulate the failure process of rock during mechanical cutting incorporating appropriate three-dimensional rock fracture,

(2) to formulate, through the computer simulation, rules for economic cutting in coal and coal measure rock materials. the development of drum lacing design software to reduce significantly pick wear and machine down time due to excessive vibration during cutting and to improve loading efficiency by:
   - creating a database of the best performing cutting machines in coal mines,
   - developing software to run on modern Windows based PC’s,
   - analysing examples of current drums designs, and by revising the software if necessary.

### 2.2.1 Modelling methodology for optimisation of the cutting process

The modelling has demonstrated that FLAC3D can be successfully used to predict the cutting force when a mechanical pick initiates breakage in rock. The chipping failure mechanism indicated by FLAC3D is one of shear to adjacent free surfaces and the relevant rock parameters, based on the Mohr Coulomb failure criterion, are the cohesion and angle of friction. Using this mechanism and by varying these parameters the essential features of experimental rock cutting studies can be reproduced including the chipping force magnitude, variation of cutting force with pick wedge angle, pick width, depth of cut and cut spacing.

The real mechanism of failure is likely to be much more complex than predicted by FLAC3D, involving a combination of shear and tensile failure processes and evidence suggests that it involves formation of a compacted crushed zone through which forces are transmitted. The geometry, properties and behaviour of this zone are currently unknown and consequently attempts to simulate its behaviour through more complex mathematical modelling processes are speculative. The successful use of shear strength parameters to predict cutting forces however suggests that shear may be the dominant mechanism in rock cutting. It is noted that other workers have found shear parameters to be closely linked to drag pick cutting.

The FLAC modelling can be used to determine pick force equations for a given rock material which quantify the relation between force components and cross sectional area of rock removed. These equations can be input to the drum design software, also developed under this project. Starting from the rock triaxial properties, it is therefore potentially possible to predict the machine capacity (power and thrust forces) required to excavate the rock at the planned production rate. The quantification of pick forces and specific energy for realistic cutting geometries, using the approach described in the Deliverable 2.1 *Methodology to analyse the failure mechanisms of rock under mechanical tools*, marks a significant advance compared with conventional laboratory testing.

### 2.2.2 Software Development for Drum Design

The review of drum designs gave an overview of the advance in drum technology since the 1980's, namely, the introduction of continuous miners and transverse roadheaders with increased machine power. The collation of the database of actual drum designs (lacings) was dependant upon the response of companies and mines from whom they were requested which was beyond the control of RMT. As the response was poor the collation of data was extended from month 12 to the end of the project at month 36 in order to maximise the information potentially available. This did not affect the progress of the project as sufficient data was acquired during the early stages of the project for software specification and development. An initial working version of the software was developed which allowed 3D visualisation of a cutting drum, breakout patterns analysis and display of the calculated force balances on the drum. This was for continuous miners and transverse roadheaders as well as axial roadheaders and shearers.

### 2.2.3 Analysis of Current Drum Designs by the New Software and Software Revision

Under this task further drum designs were analysed and the software revised. The initial working version of the software did not incorporate the capability of analysing the sumping action of an axial roadheader and the slewing action of a transverse roadheader. This was achieved under the software revision along with use of a more future proof programming language, Microsoft's .Net2.0. This software can be used to design drum lacings from scratch for effective cutting to reduce pick wear and machine down time due to excessive vibration, or can be used to analyse existing drum designs with the objective of improving efficiency.

As part of the drum design analysis, practical design tools and field applications were investigated and trialled in order to optimise the performance of current drum designs in use. This has led to a suitable methodology for drum design optimisation incorporating the following stages which specific field studies have shown to be an effective process: '

'Stage 1' Site and Drum Analysis studies to determine the factors contributing to poor cutting performance (pick consumption surveys, rock property tests on the coal and any stone bands cut, rock property data from numerical modelling, metallurgical tests of the picks, thermal imaging of the drum and CAD analysis of the drum design using the new software).

Stage 2' Drum re-design/optimisation using CAD analysis based on the 'Stage 1' information.

'Stage 3' Further pick consumption and thermal imaging surveys to confirm improved performance and identify any other potentially beneficial changes.

The software and numerical modelling successfully developed has been applied to coal cutting in underground mines within this project. However it has the flexibility to be used for other applications as it can accommodate a range of drum geometries and rock properties.

### 2.2.4 Results Dissemination

RMT, now Golder RMT, has a network of connections within the industry and clients have been alerted to the improved capability. Currently RMT are advising a European client on the cuttability of roof and floor rock for a new mining prospect, later work may include specific designs for rock cutting. An abstract has been written for submission to a conference in order to disseminate the results to a worldwide audience. This will be either the 11th AusIMMM Underground Operators' Conference, 21-23 March 2011, Canberra or Aachen, 2011 at the Sustainable Development Indicators in the Minerals Industry Conference 14-17 June. The paper is therefore planned for publication in 2011.

## 2.3 NEW METHODS FOR MONITORING/DIAGNOSTIC OF MACHINE OPERATIONS/CONDITIONS, MAINTENANCE AND MAINTAINABILITY (WP3)

The objective of this work package was to improve preventive machine maintenance and its safety implications. Hence an innovative system (software and hardware) for monitoring and visualisation of operation of the entire longwall system was to be developed allowing the diagnosis of pre-failure conditions of machines and equipment in the longwall.

For online monitoring of critical machine parameters a smart sensor network for multipoint simultaneous measurements was to be developed. All monitoring equipment was to be integrated with the graphical visualisation interface, to enable the visualization of all vital diagnostic parameters.

This research was to be complimented by the development of a maintainability assessment procedure, designed to assess both the production and safety implications of maintenance operations. The procedure should help to overcome existing practical difficulties and limitations and indicate where design changes to improve maintainability are worthy of consideration and predict the potential benefits.

### 2.3.1 Development of monitoring and visualisation of machinery systems operations and machinery contamination control

A monitoring and visualization system for longwall operations was developed, which enables the collection, processing and analysis of data from all longwall system devices. The system has been divided into synoptic screens referring to each device operating in the longwall panel. The software permits easy and semi-automatic arrangement of the visualization screens and the process data base enabling rapid adaptation of the visualization to the user's requirements.

A diagnostics system (NEMAEQ SDA) was developed along with the visualization system. This software facilitates the collection and processing of measured data, and identification of the most significant failures encountered on longwall system devices. Separation of the diagnostics system from the main visualization elements further increases its value to the industry, as installation and configuration is easier and faster than installation of an entire visualization system. The diagnostics system can cooperate with any other data processing and monitoring system used on a longwall system.

An analysis of oil contamination classes and causes was undertaken and reported D3.2 *Investigation / Recommendations on Candidate Methods of Oil Contamination Monitoring*. It was concluded that capacitive methods offer the best compromise solution, taking into account factors such as sensitivity, accuracy, low-complexity, durability, and low maintenance overhead.

### 2.3.2 Development of monitoring hardware (thermal imaging camera, wireless sensors, water in oil transducer

Prototypes of innovative diagnostic devices were successfully developed. A portable thermal imaging camera, characterised by good thermal resolution (NETD<80mK), low power consumption (<2W) and a design meeting the requirements of EN60079-11 and EN60079-0 standards, was successfully developed and assessed, feasible for submission to ATEX group I M1. Complementing its primary application, which is preventive maintenance of electrical and mechanical equipment [1], the camera also has potential in many other fields of the mining industry [2] [3], such as detection of endogenous fires and rescue action support (i.e. wayfinding through smoke, casualty location). Low power wireless diagnostic sensors, enabling the online monitoring of tri-axial vibration levels and spectrum, temperature, leak detection and water in oil content were developed, together with the appropriate interfaces and embedded control and visualisation software. The sensor solutions developed offer access to a wireless network by means of standard interfaces which facilitate future integration with machine monitoring systems from different vendors. A survey was conducted to establish which gearbox and hydraulic oil types are in common use and should be used for testing purposes. A test rig was designed, built and commissioned and a programme of experimental work undertaken to evaluate the comparative performance of six commercially available sensors. A sensor that met the measurement performance required by the industry was identified and its potential for use in practical mining applications investigated. Whilst it was found to be technically feasible to adapt this commercial product to meet the needs of the industry, realisation of this objective was uncertain and, at best, likely to result in long lead times before the benefits are realised. Consequently, an alternative approach that would facilitate a more immediate practical implementation strategy was investigated and close collaboration between partners led to the development of a proof-of-concept prototype sensor that would more readily meet the industry’s needs.

Tests of the prototype water-in-oil sensor developed by the project, combined with its ultra low power design, indicate that the time required for the practical implementation of a final product which has been designed to meet mining applications needs will be greatly reduced.

### 2.3.3 Identification and delineation of existing maintainability issues and limitations

Existing maintenance operations on coal face equipment were studied, both in Poland and the UK, to identify the operational task requirements and maintenance limitations likely to arise as a result of equipment design or the working environment in which the maintenance is undertaken.
An extensive range of maintainability limitations, imposed both by the working environment and equipment design, were identified and it was concluded that to enable an overall assessment of maintainability for a given machine it is necessary to consider the interactions between the range of maintenance tasks typically required to install and maintain machines at their optimum operational efficiency and the factors that are likely to influence the performance of the artisans conducting these tasks.

Data derived from the examination of maintenance tasks enabled the identification and definition of the key characteristics of a generic set of maintenance task elements and hence has provided the baseline data required under chapter 2.3.4 to facilitate the development of maintainability assessment tools.

### 2.3.4 Development of Maintainability and Human Reliability assessment tools

Maintainability and human reliability techniques were examined, refined and developed to produce an integrated software tool kit. The primary element of this tool kit provides a metric, a maintainability “score”, which will allow the industry to:

- Compare maintainability across machines with similar functions, hence aiding equipment selection.
- Assess the impact of potential design improvements/retro-fit modifications, to improve maintainability and hence improve production performance and reliability.
- Assess the physical effort required from maintenance staff. This assessment, combined with a measure of the artisans’ perceived “importance” of doing the task correctly can be employed to provide an indication of human reliability.
- Identify the potential for health and safety risks and critical human errors to arise.

The primary maintainability assessment tool allows virtually any of the mining maintenance tasks typically undertaken across a wide range of production and safety critical items of mining equipment, to be evaluated. Feedback from industry users (Task 5.3, see chapter 2.5.3) was used to identify the preferred interface design elements and enhance usability throughout the development process. As a result, this assessment tool was shown to be suitable for used by a wide range of industry maintenance personnel.
Additional software modules allow estimates of risks to be included directly into the maintainability assessment analysis structure and the potential for procedural violations to be assessed. These facilities serve to provide the additional information required by human factors specialists to investigate and reduce the potential for human errors to arise in situations where industry users identify the need for additional specialist assistance in solving reliability problems.

## 2.4 DATA TRANSMISSION BY FO BASED FIELDBUS-SYSTEMS (WP4)

The main target of this work package was the development of a fiber optic based fieldbus system for universal application, i.e. suitable for the automation of longwall equipment as well as new monitoring/diagnostic of machine conditions. In order to obtain this objective, the following goals were established:

- develop a cabling system, including fast and robust mining connectors for fiber-optic based fieldbuses,
- develop the physical interfaces for different applications complementary to the above cabling system,
- develop the software needed for handling the system, specially for testing purposes.

### 2.4.1 Basic Research and Technology Selection

First a detailed definition of the communication needs of current mining automation, monitoring, control and streaming (voice, video) applications were carried out. Then, a system based on the standard IEEE 802.3u, which had proved for more than 10 years demonstrating to be robust enough in both domestically and industrial fields, was designed; allowing to get an open system for the future integration of a wide range new services into the same communication network.

The selection of the suitable transmitting media is another key point in order for getting a feasible design and a reliable product. A compilation of different types of fiber optic available on the market revealed multimode, glass core, 50/125um as fulfilling best the previously defined system requirements. The use of multi-mode fiber instead of a single-mode one already means a difference respect to the communication systems currently installed in mines, where the fiber optic only is used to cover long hauls between the central station and some distribution points located underground, therefore introducing the new concept of “tactical system”, expanding the advantages of using an optical transmission media from the top to the base of the data transmission structure (or tree).

### 2.4.2 Connector and Cabling development

In order to allow the use of fiber optic in a harsh mining environment, a new connectorization method was developed. Although similar products are available on the market for military or spatial applications, the high cost and the fact that they can be only factory-assembled, do not allow their use in the target application. After considering various methods to implement the fiber contact, finally a design using a beam expander was selected as the most suitable one. The relative low cost of the materials and the strict but feasible mechanical tolerances allowable during the manufacturing process made this method relatively “easy” to be developed and applied to mining field.

The result is a [relatively] low cost fiber optic contact, capable of being assembled in field and of withstand the physical aggressions of the harsh working environment. Although several modifications were performed on the original design and numerous prototypes were developed in the labs (only some of them with successful results), the final product is almost ready to be marketed.

The integration of fiber optic and copper in the same cable is an essential concept to get a fieldbus based communication architecture. To achieve that, a new mixed connectoring and cabling system was developed, including power supply, wired data transmission lines and optical wires integrated into a single connector covered by robust stainless steel shell. Taking advantage of the know-how gained from both several years of development of mining connectoring systems and from the new research performed in the optic field during the project, the result of the work performed is a mixed connector and cabling system incorporating both endurance strength and excellent communication capabilities.

### 2.4.3 Interfaces development

The integration of different devices into a common communication network based on fiber optic requires an interface between the optical media and the equipment to be connected. Two innovations have been performed in this field. The first one is the development of a universal interface/media converter intended for tactical applications. This device includes fiber optic contacts for harsh environment operation and a flexible intrinsically safe interface to connect peripherals/modules. It acts as a bridge between the fiber and multiple protocols/communication ports, both wired and wireless, e.g. WiFi access points, PAN based systems (as the developed in RAINOW project RFCR-CT-2005-00003, current process controls using RS485 fieldbus, etc).

These devices, especially designed for tactical applications, where changes in the physical location and network organization are frequently performed, can be accessed both locally and remotely using dedicated software applications. In addition, and due to the fact that these kind of communication infrastructures are designed for providing support to critical systems as environmental monitoring or ventilation control, they are equipped with safety features as redundancy management or alarm trigger capabilities (in case that some malfunction is detected).

The second innovation also related with the safety in communication systems, consists in performing some improvements on the currently used trunk fiber systems. The WDM (Wavelength Division Multiplexing) concept has been introduced in that kind of systems developing a new fiber optic interface. This new device is capable of transmitting and receiving the information using a single strand fiber optic. It means that one of the fibers of the usually double (or more) strand of fiber cables installed in mines as communication backbone can be used as secure path, allowing the implementation of a ring topology without installing supplementary lengths of fiber cable, saving costs and increasing the global exploitation safety.

Both the tactical interfaces and WDM devices are expected to be commercialised within the next months by AITEMIN and EMAG respectively.

### 2.4.4 Software development

The management of the configuration parameters in a communication network that is frequently changed in response to the exploitations requirements, requires specific software, which should also be able of providing a global view of the status of the whole communication system. In order to achieve that, a configuration and managing software tool was developed. This application uses the Simple Network Management Protocol (SNMP), which is a standard tool used by computer network administrators to access the internal parameters of the interfaces distributed along the whole network from a remote station (usually the control room). This software is based on a database engine, and as an advantage over another solutions, ensures the automatic monitoring of network devices using an easy and friendly graphical interface.
The required embedded control software for WDM interfaces was also developed. It performs the configuration and supervision tasks as well as enables configuration of serial auxiliary interfaces and IP connectivity settings.

## 2.5 UNDERGROUND TESTING (WP5)

The objective of this work package was to harmonise the data transfer system with the requirements of the automatic shearer loader system as well as the visualization and monitoring system. All data are to be compiled in an appropriate manner to integrate them into the software system used in the mining control room. The aim of this WP was to test and optimise the results of WP1, WP3 and WP4:

- Testing data bus system
- Testing the visualization and monitoring system
- Testing of assessment tools and identification of approaches to improve human reliability
- Testing of the full automatic shearer loader operations under real conditions

### 2.5.1 Field Tests of Databus system

An experimental installation using the devices based on fiber optic developed during the project was performed in the labor school of “El Bierzo”, located in León (Spain) and belonging to “Fundación Santa Bárbara”. During the trials, fiber optic contacts for harsh environment, mixed cables, mixed connectors and FO interfaces were used together, making up a communication system with a fieldbus topology, getting all the benefits provided by an optical media and, at the same time, keeping the robustness and reliability of other systems based on copper wires.

During the trials, the monitoring and control systems existing in the installation were easily integrated into the new optic fieldbus, improving their functionality, and some typical problems as the high background noise in long analog voice lines were solved using digital speech systems. In addition, new services as IP video cameras were added to the exploitation.
Currently, “Fundación Santa Bárbara” is employing part of the equipment used during the trials during their daily works and a fiber optic network using these devices is expected to be installed in some HUNOSA’s mines. Tests of the databus system components carried out in Guido mine Zabrze (Poland) enabled to improve the data collection scheme of wireless vibration sensors and proved correct operation of particular transmission system components.

### 2.5.2 Testing the visualization and monitoring system in a selected mine

The test installation deployed in Guido mine made it possible to carry out functional tests of the databus system, monitoring devices and the associated visualisation/remote management software. The test configuration enabled both local and remote operation of high level part of the monitoring system. The overall results were satisfactory and the deployed system operated reliably. What is important the observations and conclusions derived from the early stage of the tests were taken into consideration in final bug-fixing and optimisation.

### 2.5.3 Testing of assessment tools and identification of approaches to improve human reliability

Field trials and evaluation exercises were undertaken with the assistance of mining maintenance managers, supervisors and artisan’s throughout the maintainability software development process (chapter 2.3.3). The on-going involvement of, and collaboration with, representatives of the industry who were directly involved in practical mining maintenance operations served to validate, confirm and optimise the usability and practical utility of the toolkit assessment techniques and final software product.

### 2.5.4 Linking of monitoring and control technology for the fully automated control of shearer loader operations and underground field test

Besides underground tests of single sensors and subsystems one field test of the whole automation system took place during the project at Prosper Colliery to check the overall functional capability and to record data for offline software improvements and determination of parameters. The findings also enabled a series of major improvements and adjustments which could be realized in the workshop phase between January and April 2009 as a precondition for the implementation of the project result. After the project end, the revised shearer was subjected to a final test in October 2009 at Auguste Victoria Colliery in which the applicability of the whole system could be demonstrated convincingly.

The IR sensors itself were successfully tested for their overall functionality. The system proved its general efficiency and robustness. Extremely irregular and unstructured geological textures causing detection problems initiated the successful development of additional filters criterions. After several revisions an optimal positioning of the IR sensor box could be found.

The radar - sensor and the appropriate evaluation software proved their applicability, too. The radar detected objects in the defined collision area early and precise enough to adjust the ranging arm position without interrupting the production. It also identified the conveyor load in time for a proactive coal flow management. Even the unavoidable dust layer at the Ge window caused no functional impairment. In order to improve the raw data quality of the sensor imposed to the adverse mine air direction and conveyor load the camera is to be mounted in the front of the monitor box instead of the edge thus preventing an occlusion of the radar device.
All other “enabling” systems e.g. Machine Gateway and Machine Server (hardware and software) as inherent parts of the automation system proved their applicability thus enabling the whole automation system to work.

# 3 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

This section covers the research approach providing a description of the experimental work performed on a task per task basis, highlighting the main results achieved.

## 3.1 OBJECTIVES OF THE PROJECT

Automation and mechanization are important key factors for increasing the performance of longwall and drivage equipment and thus reducing the production costs. To take full advantage of a higher grade of automation it is necessary to enhance the reliability of the equipment. This can be achieved by preventive, stateful methods of maintenance and easy maintainability. Hence the main objectives of this project were as follows:

- Development of a full automatic shearer loader system which facilitates the complete winning process without any manual interaction. This reduces significantly the proportion of dirt in the run-of-mine coal as 'overhead' costs and disburdens the capacity of the haulage chain.
- Attaining the most modern knowledge about rock cutting and improving significantly the cutting and loading process for coal shearers as well as for roadheaders to reduce pick wear, machine downtime due to vibrations and production of dust and fine coal/rock. The outcomes of this objective will be available in user-friendly software. This will be taken into account by design of the automatic coal shearer.
- Development of new systems for monitoring of machinery systems with modern devices to be developed and evaluation of the machine conditions in graphical visualization to enable new methods of maintenance.
- Development of a maintainability assessment tool to identify areas for potential improvement to equipment maintainability. This will allow developing measures for easy efficient maintenance work.

### 3.1.1 Automation of longwall equipment (WP1)

The overriding objective of this work package was a full automation of the shearer loader operations (steering of support arm, control of machine speed and adjustment to match the shield support control). Hence a series of technical conditions had to be met in order to ensure automatic face navigation, in particular

- Identification of the coal- rock- interface,
- Avoidance of collisions,
- Load dependent regulation of shearer loader speed and the locating of the winning equipment.

Additionally, in order to avoid operational delays due to the common manual pushing or pulling of the drives at the face ends suggestions were to be developed for the automation of face end systems based on an overview of solutions in use in the international mining industry.

### 3.1.2 Optimisation of the cutting and loading process for Coal Shearers, Continuous Miners and Axial and Transverse Roadheaders (WP2)

The objective was to improve the efficiency of cutting drums of coal shearers, continuous miners and axial and transverse roadheaders. This was to be done by:

the development of numerical models to simulate the process of mechanical rock cutting to:

- simulate the failure process of rock during mechanical cutting incorporating appropriate three-dimensional rock fracture,
- to formulate, through the computer simulation, rules for economic cutting in coal and coal measure rock materials,

- the development of drum lacing design software to reduce significantly pick wear and machine down time due to excessive vibration during cutting and to improve loading efficiency by:
- creating a database of the best performing cutting machines in coal mines,
- developing software to run on modern Windows based PC's,
- analysing examples of current drums designs, and by revising the software if necessary.

### 3.1.3 New methods for monitoring/diagnostic of machine operations/conditions, maintenance and maintainability (WP3)

The overriding objective of this work package was to improve preventive machine maintenance operations. Hence, an innovative system for monitoring and visualisation of the entire longwall system was to be developed that allowed pre-failure conditions of equipment to be diagnosed. To meet this objective hardware devices for monitoring and preventive maintenance applications had to be developed (explosion-proof, portable thermal imaging camera and online water in oil transducer).

For online monitoring of critical machine parameters a smart sensor network for multipoint simultaneous measurements was to be developed that could be integrated with the monitoring and visualisation system and provide vital diagnostic parameters.

These works were to be complemented by the development of maintainability assessment techniques to assess production and safety implications of maintenance operations. These techniques should help overcome existing practical difficulties and limitations and indicate where design changes to improve maintainability are worthy of consideration and predict the potential benefits.

### 3.1.4 Data transmission by FO based Fieldbus-Systems (WP4)

The main target of this WP consisted of the development of a fiber optic based fieldbus system of universal application, i.e. suitable for the automation of longwall equipment as well as new monitoring/diagnostic of machine conditions. In order to reach this objective, the following goals were established:

- Develop a cabling system, including fast and robust mining connectors for fiber-optic based fieldbuses,
- Develop the physical interfaces for different applications complementary to the above cabling system,
- Develop the software needed for handling the system, especially for testing purposes.

### 3.1.5 Underground testing (WP5)

The objective of this work package was to harmonise the data transfer system with the requirements of the automatic shearer loader system as well as the visualization and monitoring system. All data are to be compiled in an appropriate manner to integrate them into the software system used in the mining control room. The aim of this WP was to test and optimise the results of WP1, WP3 and WP4:

- Testing data bus system
- Testing the visualization and monitoring system
- Testing of assessment tools and identification of approaches to improve human reliability
- Testing of the full automatic shearer loader operations under real conditions

## 3.2 COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED

This section provides a comparison of initially planned activities and work accomplished. Any major deviations from the initial plan and their effects on the project are described.

### 3.2.1 Automation of longwall equipment (WP1)

The major deviation concerns the early termination of the University's of Clausthal participation as from 9 July 2008. With this decision the Commissions Services followed the assessment of TGC 1 that the University's research work was significantly different from what was defined as task in the Technical Annex. Instead of "Design of automatic pushing devices for the drives"Deliverable D1.3 covers "Face End and Automation Technologies".

All other variations from the initial planning were caused by new findings typical for risky research projects and aimed at the achievement of the original project objectives: Contrary to initial planning two IR sensors instead of one were necessary to detect the coal- rock boundary over the whole seam section. The radar sensor developed earlier in a monorail application for obstacle detection turned out to be not applicable under the longwall environment. Hence as an alternative a radar sensor with a higher resolution was identified and adapted successfully. During the underground tests it showed that additional to initial planning a video control was necessary by safety reasons when operating the shearer automatically. Shearer location with wireless sensor nodes turned out to be too sophisticated and not accurate enough. Instead an easier and more exact solution using magnet switches was developed.

### 3.2.2 Optimisation of the cutting and loading process for Coal Shearers, Continuous Miners and Axial and Transverse Roadheaders (WP2)

The collation of a database of drum designs in current use worldwide, which was necessary to validate and refine the drum design software, proved extremely difficult to obtain. Deliverable 2.2 is therefore less comprehensive than anticipated, however sufficient data was obtained for software development to be completed as planned within the project.

It is planned that a paper shall be written for submission for a Conference for results dissemination to a wider audience beyond RMT's extensive contacts. This could not be completed during the time scale of the project as the research continued up to the completion of the project in June 2009.  It is planned to be published and presented in 2011.

### 3.2.3 New methods for monitoring/diagnostic of machine operations/ conditions, maintenance and maintainability (WP3)

One minor diversion occurred due to the fact that the evaluation and testing of commercially available water in oil sensors described in chapter 3.3.3.1 indicated that suitable devices were already potential available for use by the industry. However, despite the fact that it was found to be technically feasible to adapt existing products to produce ATEX M1 or M2 certificated sensors, discussions with suppliers indicated that commercial considerations were likely to result in long lead times at best.

Furthermore, it was found that there were significant practical problems in terms of retrofitting longwall equipment to accommodate these sensors. Consequently, the project partners collaborated to upgrade and enhance the "water presence/level" sensor developed (see chapter 3.3.3.2) and produce an alternative transducer to sense water in oil. Comparative tests of this project innovation showed that the performance is comparable with the best of the commercially available devices tested and practical implementation restrictions are likely to be significantly reduced. Hence, this minor variation from the original project plan has had no adverse impact; the intended objectives have been met and ultimately a more beneficial industry solution derived.

### 3.2.4 Data transmission by FO based Fieldbus-Systems (WP4)

The development of a mixed connector and specially the fiber optic contact was delayed due to difficulties found in -and long time devoted to- the machining (turning, milling and polishing) processes. Main difficulties were related with the requirement of high accuracy (low mechanical tolerances) and the impossibility of performing the work in a professional workshop.

Initially a test in Guido mine was planned for both tactical and WDM interfaces in order to check the interoperability between them. Unfortunately ICP, the supplier and manufacturer of the mixed connector who was also involved in the development, stopped business before finishing the first batch of mixed contacts. Consequently Aitemin started a connector production at its own, but due to the related delay it was not possible to perform the planned tests during the project. The approach of the software development regarding to the tactical FO interfaces was changed when commercial devices were used to implementing the apparatus. No embedded firmware development is needed for these interfaces.

### 3.2.5 Underground testing (WP5)

Originally the SCADA visualization system was to be tested underground communicating directly with the long-wall equipment. During the project execution however insufficient data transmission mine infrastructure challenged an online data transmission. In order to enable test the SCADA System in spite of that it was tested with real underground machine data which had been recorded on memory cards before. For the tests this made no difference as process variables matter and not the way of data collection. This diversion even enabled to carry out the test on a broader data basis i.e. for two types of machines operating in four different hard coal mines and thus extended the scope of the testing.

## 3.3 DESCRIPTION OF ACTIVITIES & DISCUSSION

This section describes the project activities and highlights the innovations made.

### 3.3.1 Automation of longwall equipment (WP1)

#### 3.3.1.1 Determination or establishment of the parameters to be observed and the state of the art and knowledge from previous projects

As a basis for all following steps and to identify candidate technologies for shearer loader automation, the work started with a review of previous research projects and of sensor technologies for the recognition of coal / rock interface, collision avoidance, load-dependent speed regulation and shearer loader location. Experiences with embedded systems technologies in underground hard coal mining applications as well as software and algorithms suitable for the targeted applications were compiled and assessed in order to identify appropriate and secure technologies for the integration of the IT systems on the shearer into the mine's corporate networking infrastructure.

***Coal/rock interface detection***

The data to be obtained here are necessary to steer the shearers cutting drums automatically along the interface between coal and rock. The analysis of publications and earlier experiences on coal – rock - interface detection principles led to the following surface based, saturating methods carrying a basic potential for applicability.

(a) Laser Induced Fluorescence (LIF)
(b) Chisel Force Logging
(c) Geo Electricity
(e) Natural Gamma Radiation
(f) Optical Sensor
(g) Seismic Measurements
(h) Thermal Performance
(i) Geo Radar
(k) Impact Sound
(l) Infra Red Measuring

As a result of detailed investigations and of laboratory and underground tests Impact Sound and Infrared Measuring turned out to be most appropriate and were developed further (see Task 1.2, chapter 3.3.1.2).

The reasons why the other methods had to be dropped are given in ***appendix 6.1.1, page 119.***

***Collision Avoidance and Shearer Location***

Collision avoidance is an indispensable precondition for shearer automation. It concerns the detection of obstacles in the face conveyor and of shield canopies protruding in the face conveyor, the proper identification of the conveyor end and the localisation of the shearer position in order to stop the shearer early enough at the face end or in front of an obstacle.
For detection of obstacles laser scanners and ultrasonic sensors were taken into account first. More detailed investigations however showed that the applicability of laser scanners is limited due to strong vibrations at the shearer loader. That is why this technology had to be dropped. Ultrasonic sensors are - besides of a limited measuring range – very sensitive for wind. Due to a typically narrow air diameter in the face - particularly in the shearer loader area - the conditions turned out to be not suitable for obstacle detection with this technology, which had to be dropped, too.

According to positive experience from an earlier project Ultra Wideband Radar sensors seemed to be more promising. In that monorail application the radar sensor had shown excellent usability for obstacle detection. Therefore the certification for this radar sensor was extended and modified in order to allow universal use in underground coal mines.

For shearer loader location first orientating experiments at the surface were conducted using synchronisation switches at the shearer loader and magnets at the conveyor ends the position of the latter taking into account the position of the respective shearer drum. As the preliminary results were promising this development was continued under Task 1.2 (see chapter 3.3.1.2).

As another way of shearer loader location wireless sensor network technology with ranging capabilities, mainly foreseen to be used in WP3 for the shearer loader monitoring was taken into consideration, too. The principle of operation is based on the capability of distance measurement between mobile nodes located on the shearer and reference nodes bound to particular pieces of equipment at the face. The measurement of the relative distance is based on multiple measurements of time required for data packets to travel between two nodes.

***Load Dependant Regulation of the Shearer Loader*** aims at optimal conveyor utilization. An automatic reduction of the shearer loader speed shall prevent the conveyor from overload causing downtime. A concept was designed for the cooperation among the shearer and the conveyor control subsystems which have to be connected in a network and operate within an integrated system. Parameters to be determined analysed and controlled under the regime of a comprehensive control system are shearer position, shearer velocity, cutting depth and relative speed between shearer and conveyor.

***An Onboard IT Level Computing Infrastructure*** is another precondition for shearer automation. A Machine Server as embedded computing system has to provide sensor information processing, high level control and shearer communication and the integration of the IT systems on the shearer into the mine's corporate networking infrastructure. Starting from existing platforms developed in earlier projects a prototype system was set up as with CPU module including a wired Ethernet port to connect automation systems on the machine, interfaces for communication with the longwall WLAN infrastructure and couplers for external antennas not residing inside the flameproof housing. Optional possibilities exist to add video digitizer cards and other extensions to the Machine Server hardware.

Hardware and software were prepared for the following tasks which were to be accomplished under Task 1.2 (see chapter 3.3.1.2).

- Development of an interfacing and visualisation software running on the Machine Server
- Development of an optimized WLAN roaming for the Machine Server in order to comply with the demands of the moving shearer.

***Figure 3.3.1-1: WLAN Machine Server***

The determination and the establishment of the parameters to be observed was finished according to project plan within the first half year. The state of the art and the knowledge from previous projects were acquired and were reflected in Task 1.2 (see chapter 3.3.1.2).

### 3.3.1.2 Recognition of coal/surrounding rock interface, collision avoidance, load- dependent speed regulation and shearer loader location

***Coal/rock interface detection***

***Infra Red Measuring***

According to the review accomplished under Task 1.1 (see chapter 3.3.1.1), different cutting forces and different thermal conductivity of coal and rock turned out to be feasible for layer detection with IR sensors. Laboratory tests demonstrated this vividly (***figure 3.3.1-2**, *next page**). Based on these findings first IR sensors were acquired and tested underground.

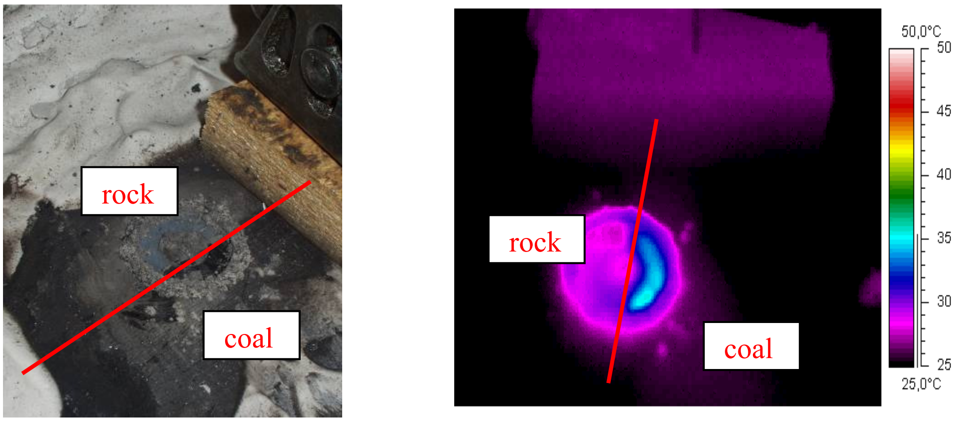
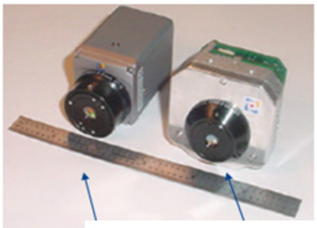



*Figure 3.3.1-2: for laboratory test on infra red measurement with drilling machine (left) and result (right): infra red image 20'' after drilling*

The raw data recorded during these underground tests revealed structure characteristics which confirmed the applicability. That is why further cameras were tested for their infrared sensors in the laboratory and underground. ***Figure 3.3.1-3*** shows an early (left) and the IR sensor finally applied.



| | Old Sensor | New Sensor | |
|---|---|---|---|
| Resolution (Px) | 160 x 128 | 160 x 128 | 320 x 240 |
| Focal Width (mm) | 8,5 | 6,3 | 14,25 |
| Field of View | 55° x 41,8° | 52° x 40° | 46° x 36° |

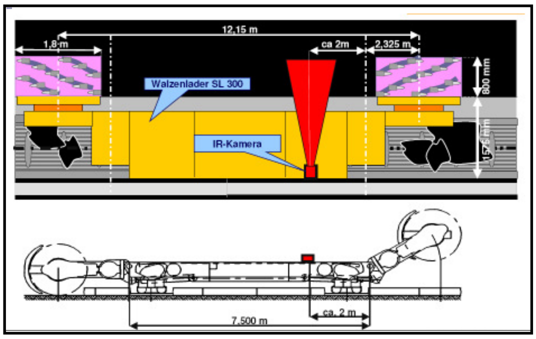



*Figure 3.3.1-3: IR sensor systems (left) and experimental set-up for underground test (right)*

The tests also affirmed that two infrared sensors are necessary to cover the whole seam thickness – one for the middle and one for the upper part of the seam. ***Figure 3.3.1-4*** shows the positions and the vision angles of the IR sensors. The vision angle of camera 1 is directed towards the roof whereas that of camera 2 is directed towards the coalface. The boundary layer has to be detected by impact sound sensors due to broken coal and rock on the ground averting an IR measurement

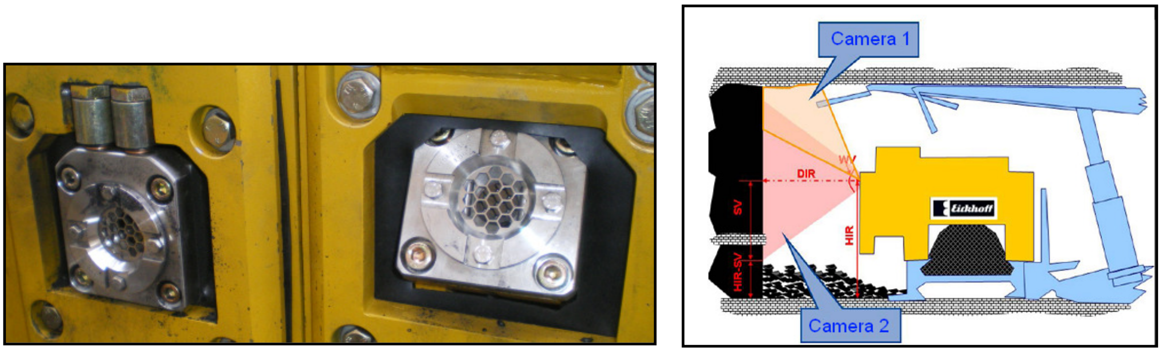



*Figure 3.3.1-4: Inclined IR sensors with protective grill and vision angles*

***IR image processing and program development***
Several months of operating the sensors underground provided enough raw data and high-grade IR images for the development of the algorithms for longwall image generation and boundary layer detection and a robust image processing.

For the interpretation of the infrared images a special picture editing software is used which scans the pictures in chronological sequence for common pixels. The images are then superimposed to form a continuous data stream for each travelling motion. Simultaneously, the photos are sorted out according to structure characteristics and the coordinates are measured. Following this, the data is compared in a filter with the data of previous Memory Cuts[1] and passed to the shearers control system.

Both the control software and the data acquisition facility of the IR camera are activated by the Shearers on board computer. The camera is triggered as a function of the shearer loader position. The recorded infrared picture data is provided with a position-dependant stamp and thus correlated with the shearer loader position, and saved in the destination folder of the onboard IR Industry PC (IPC). While the shearer is cutting the face end area the IPC analyses the pictures of the complete face.

To this end the saved IR pictures are put together to one longwall image and processed for coal interface detection by means of an algorithm. To enable longwall image generation, a Region of Interest (ROI) of X pixels is defined and cropped for each picture by the image processing system. Thereafter, the ROIs are stitched to eliminate stair-stepping and fisheye effects. The recorded pictures are processed and improved to eliminate faults caused by the physics of image generation and digitalisation as far as possible (***figure 3.3.1-5***). Further details on the data processing are given under ***6.1.1, page 119 ff.***

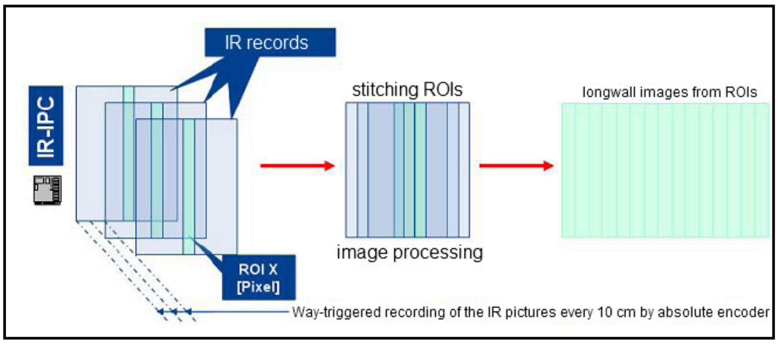



***Figure 3.3.1-5: Face image put together from ROIs***

The progress obtained in optimizing and generating longwall images during the project is obvious in a comparison between the longwall images produced in different states of development ***(figure 3.3.1-6)***: In the first image taken on September 2006 the very thick leading belt can be identified; the image section was manually stitched together. The second image was taken in July 2007 and was automatically stitched together. The third image was taken in October 2008, automatically stitched, too. The individual images overlap correctly so that the line structures of the searched marker bands are maintained. The difficult geological conditions and the covering of the leading layer package with cut material are clearly visible.

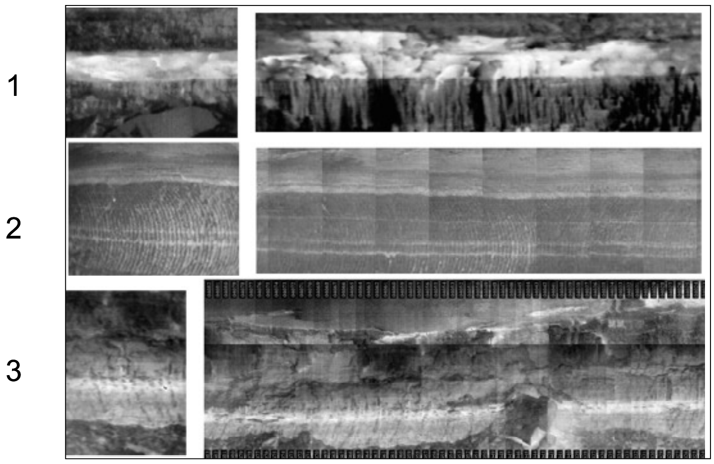



***Figure 3.3.1-6: Improvement of IR images quality taken in several states of development***

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[1] **Memory Cut**: The shearer's board computer stores the position of the manually steered ranging arm in correlation with the shearer's position in the face in order to use it for following cuts.

***Manual Interface Following Tool***
Despite these good results the automatic boundary detection has its limits in the geology. A tool for manual coal interface following was therefore developed which also provides a visualization of the IR-face images filed. This tool enables the operator to perform coal interface detection even under poor geological conditions ***(figure 3.3.1-7)***. It assists the operator to take over and to perform the coal interface detection. In addition it can be used for the calibration of the automatic function and to revise and verify mine surveying and geological data.

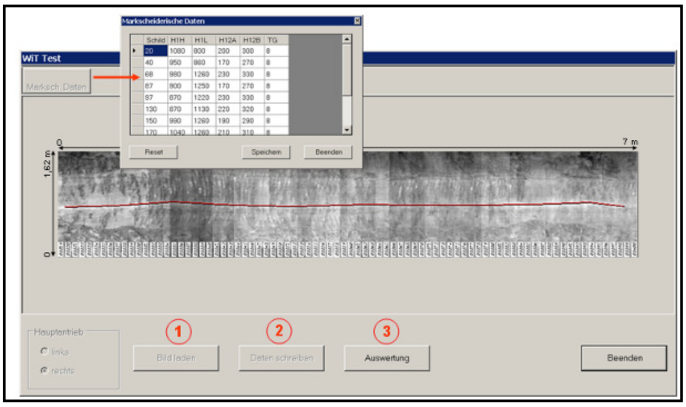


***Figure 3.3.1-7: Manual coal interface detection tool***

The tool can also be used to access an archiving folder for face images so that specified images can be displayed and analysed. Furthermore it allows performing the face analysis and shearer programming by one central expert, a task which takes only 5 minutes every hour per longwall, so that one expert can control 20 longwalls. This improves the decision in terms of quality management, helps to monitor results and reduces the variance of a individual operators within at the various coal mines.

***Sensor Box and Water Spray System***
A particular issue was the protection of all components of the IR camera in a sensor box and its lens in the harsh underground environment. A germanium window was selected therefore which in turn is protected against stone chipping by a grill ***(figure 3.3.1-8)***. An impulse water spray system with conical spray nozzles proved best for cleaning the germanium window. It is capable of removing coarse deposits from the window. The signal for the water spray facility is checked by the IR IPC. During the cleaning operation the recording of the IR images is interrupted and texture- free dummy pictures are saved so that the water spray system cannot irritate the evaluation.

***Figure 3.3.1-8: Germanium window with protective grill and water spray system (right)***

After several months of underground use laboratory analyses revealed chemical corrosion on the germanium window. Fine hairline cracks were presumed to develop in the DLC coating of the window allowing the dirt deposits to penetrate below the surface, to react with the mine water and thus to creep into the glass. ***Figure 3.3.1-9****, next page* shows the chemical corrosion and a microscope image of the corroded spots. Efforts to protect the germanium window by polycarbonate coatings did not prove[2]. Consequently the Ge window has to be replaced in the framework of the periodic maintenance.

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[2] Stone chipping and spray water detached the coating after a short period of underground use. Moreover, the bonding process turned out to be very laborious and complex so that this protecting method did not prove. The same applied for Lotus effect coatings.

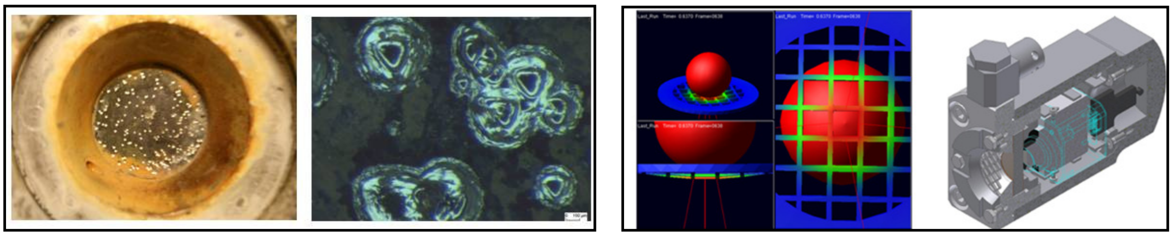


*Figure 3.3.1-9: Pitting Corrosion on the Ge Window; Implemented Grill; Load Analysis Algorithm (right)*

Various grid forms and shapes were designed and tested to ensure the drain of particles sticking between the window and the grid influencing the IR images. By simulating the drop test and the impact of the particles through load analyses, the grids were designed in such a manner that approval could be obtained[3]. ***Figure 3.3.1-9*** shows a simulation of the drop tests and the stress analysis of the implemented grill; at the very right the complete IR-Camera module as a 3D model.

***Impact Sound***
It is difficult to identify the boundary between the seam and the floor with IR sensors as this area often is covered by cut coal. That is why impact sound sensors were tested starting from the idea that cutting of rock in the floor causes stronger or at least different vibrations and sounds than cutting coal. Several sensors were mounted to the ranging arm of a shearer underground ***(figure 3.3.1-10)***. The data were analysed and interpreted.

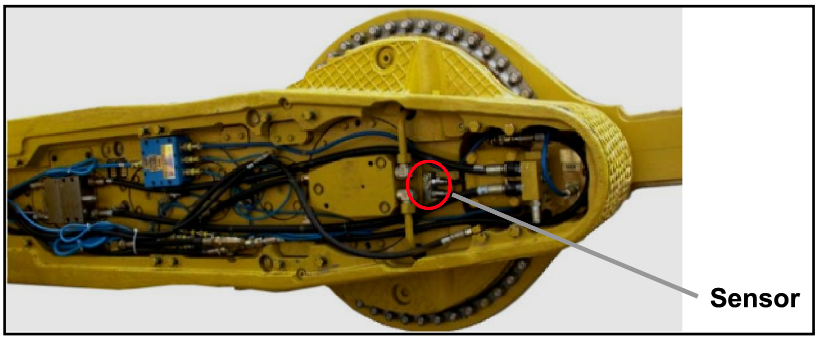



***Figure 3.3.1-10: Impact sensor integrated in the ranging arm***

The research focussed at the selection of the right frequency bands in the sound spectrum and to develop a transfer function between frequency, amplitude and machine speed and the resulting rock strength as a factor describing the share of cut coal or surrounding rock. Furthermore a concept of multiplexing multiple sensors with the restricted calculation power of the processing unit had to be developed.

A visualisation tool showing the amplitude and threshold values of the last 20 seconds was programmed in the machine control user interface for easy commissioning. Furthermore the user is able to set the threshold values in various segments independently over the length of the longwall. In underground tests differences between the left and the right ranging arm could be identified, making a customized parameterization necessary. The complete system was evaluated as valuable if parameters are updated regularly.

***Collision Avoidance at Face Ends***
Collision avoidance between the shearer ranging arm and conveyor drivers by means of timely raising of the shearer ranging arm at the face ends is mainly achieved by a proper identification of the shearer position as precondition for an exact steering and stopping of the shearer in this area.

Synchronization switches at the Shearer loader and magnets at the conveyor ends were tested successfully for this purpose at the surface with a shearer loader in connection with a face conveyor the position of the latter taking into account the position of the respective shearer drum. That is why as a next stage underground tests were carried out in 3 collieries. In all cases the results achieved were

[3] The test of the grid is necessary to show that it can resist even a large impact by rocks so that the Ge- glass below the grid stays intact which otherwise might lead to an explosion in a methane containing atmosphere.

similar: At the main drive end of the face conveyor repeatable results could be achieved. Due to the given flexibility of the conveyor pans at the auxiliary drive end which can cause a position difference up to +/- 15 cm however the test result were not satisfactory first. In order to improve the position metering the rotation of the driving gear was detected then additionally and the angles between the conveyor drive and the conveyor itself measured with potentiometers. On the basis of these data new software compensates the flexibility effect on the longimetry thus obtaining a precision of +/- 1cm. The improved system was tested successfully and is invented in various mines meanwhile.

***Collision Avoidance in the Face***

Based on the review (chapter 3.3.1.1) investigations concentrated at radar as technology for obstacle detection. An ultra wideband radar sensor which had proven its applicability for monorail automation in roadways was investigated first. Although this 24 GHz SLR sensor revealed its basic functionality in the laboratory sensor turned out to be not appropriate in the longwall: According training mine tests the resolution is not high enough to detect low hanging shields and to carry out other longwall shearer relevant detection purposes. Hence the partners decided to adapt a radar sensor with a higher resolution originating from the automotive sector. The 24 GHz sensor sensor is however available now and certified including related machine server software for general obstacle detection tasks within coal mining e.g. to detect profile clearance on transport equipment.

In comprehensive test series with various radar types a 77GHz dual-range radar (DRR)[4] turned out to be applicable best. This radar sensor was positioned such that it is angle-resolving in the vertical direction. It performs two separate functions: To follow the shield canopies for collision avoidance on the one hand and to monitor the conveyor loading height to prevent blockage of the coal clearance cross-section on the other. For this purpose, the sensor performs a precise scan within a range of ±8,5° for mass flow and conveyor overload evaluation and separately for warning of imminent collisions with extremely low-lying obstacles or defective front cantilevers. A rough scan within a range of ±30° serves as conveyor monitoring only ***(figure 3.3.1-11)***.

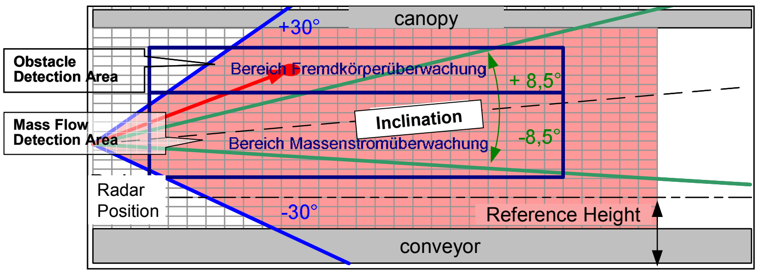



***Figure 3.3.1-11: Radar evaluation ranges***

The radar system is capable of detecting conveyor overloads thus reducing the risk of blockage of the coal clearance cross-section beneath the machine. The system also avoids collisions of the machine body with obstacles lying in the machine travelling track. In case of an imminent collision and with active control intervention, the machine stops ahead of an obstacle (haulage stop). At the same time a pop-up window with a warning message is supposed to be generated on the on-board screen.

Underground measuring series were carried out not least in order to collect sufficient data as a basis for software calibration and optimization and setting up parameters. ***Figure 3.3.1-12*** gives examples for individual pictures, and identified objects. The long red line represents the spill plates, the high blue-green areas represent the canopies at 1,75m distance. Detected objects are marked accordingly.

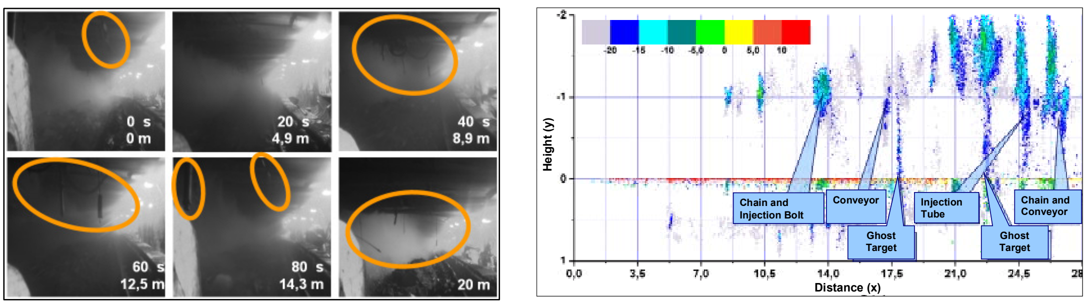



***Figure 3.3.1-12: Position [m] and time of measurement [s] identified objects are marked***

[4] Manufacturer: Indurad GmbH

As an additional technology for collision avoidance a video camera with LED headlights was tested and finally applied in order to provide the safety when the shearer is operated automatically. The video images are transferred to the surface control centre.

***Radar Housing and Sensor Arm***

The design and the positioning of the radar housing had to consider attenuation, explosion protection, multipath propagation and maximum dimensions. Due to the limited vertical coverage by the radar and the complexity reduction in the data conversion, the radar device was mounted at a fixed component[5].

Given the main lobe width in the horizontal direction of about 4°, a mounting position relatively close to the front turned out to be beneficial. Both the sensor arm and the protective motor housing had to be re-designed several times. The particular challenge was to neither impede the field of view of the radar nor affect the floodlight on the protective motor housing. ***Figure 3.3.1-13*** shows the ranging arm with the radar housing. Due to the sensor- related limitation of the vertical detection angle the radar is inclined towards the shield canopies.


***Figure 3.3.1-13: Radar, video camera and LED headlight mounted to the shearer loader***

***Gradient Issue***

The largest error is not caused by the radar sensor itself but by its permanently changing range of vision and its permanently changing height in relation to the detected shield canopies ***(figure 3.3.1-14)***.
Up to the project end the course of the face gradient recorded on the previous shear was used as an approach to compensate for this effect. This approach, however, only identifies the gradient between the shoes of the shearer loader rather than the real course of the gradient. Moreover, simple back calculations to height deviations using the gradient data are highly error afflicted. The course of the face gradient during the trial operation is given in ***figure 3.3.1-15***.

A more precise calculation applying a more complex mathematical model would be possible using an inertial navigation system as it is in use for shearer loaders in Australia. This could however not be tested during the project lifetime. Further technical details and features of the radar sensor are given under ***6.1.1, page 119 ff.***

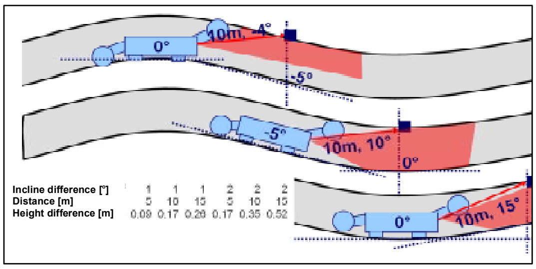



***Figure 3.3.1-14: Effect of Face Line on Canopy Table***

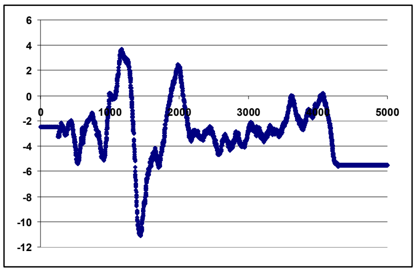



***Figure 3.3.1-15: Face Gradient***

***Location of the Shearer Loader at the Face***

Wireless sensor technology with ranging capabilities basically offers the possibility to locate the shearer relatively to 'known' objects (e.g. shield support, conveyor) tagged with reference nodes. Using triangulation techniques and a sufficient number of reference nodes two or even three dimensional

[5] Consequently the motor protective housing had to be dropped as location as it inclines with the ranging arm. A position between the shearer loader and the spill plate did not prove due to the large dimensions and the high profile. Protruding too far towards the front the sensor arm had conveyed material into the cable handler trough.

relative locations can be achieved. The relative distance is calculated from multiple measurements of the time required for data packets to travel between two wireless nodes.

The packet exchange scheme consists of two symmetrical phases. Because of the symmetry impact of time base offset errors, which would normally affect to the large extend the accuracy, can be cancelled out. Whereas the theoretical resolution of distance measurement for time base errors of local oscillators can reach 0.12m for distances from 1m up to 100m, factors as asymmetry of real implementations or jitter can diminish this accuracy. *(figure 3.3.1-16)*

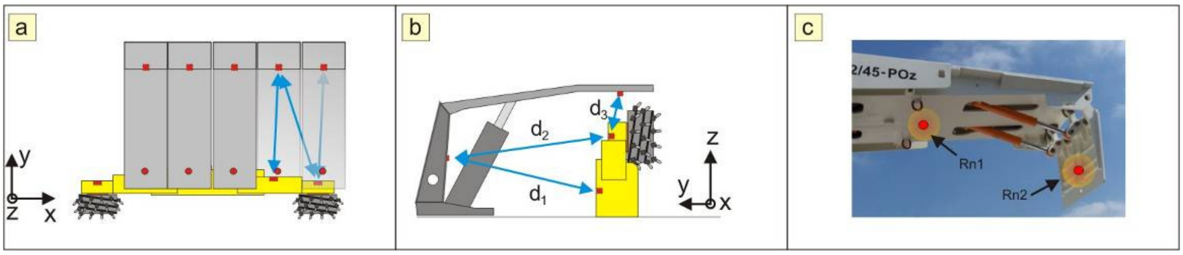



***Figure 3.3.1-16: Application of ranging features of WSN for (a) 2-D, (b) 3D-location, (c) collision avoidance***

After promising laboratory tests with a technology demonstrator additional tests were conducted in order to find the limitations of the physical implementation and to observe the impact of the propagation conditions typical of a mining environment. In the anechoic chamber the maximum accuracy reached 1m (+/- 0.5m), with multiple reference nodes due to limited accuracy of reference clocks and insufficient post-processing.

Under actual underground conditions in the Guido mine *(figure 3.3.1-17)* the average accuracy reached 2m and was degraded in certain conditions up to 3m As expected the performance dropped especially in areas with high concentration of metal debris or in places characterized by small apertures. The final error of distance measurement was caused either by the increased jitter or synchronizing to the reflected and not to the direct signal. Possibly these effects could be reduced using two or more spatially separated reference nodes or by employing aerial diversity techniques. This was judged however to be too sophisticated and expensive.


***Figure 3.3.1-17: Wireless ranking tests in Guido mine***

That is why this method was dropped for this application - especially since it appeared that the system developed for collision avoidance at face ends **(see page 26/27)** can be adapted here, too. That is to say that the rotation of the shearer driving gear is detected in order to meter the distance from magnets at the conveyor ends serving as reference points which are detected by synchronization switches at the Shearer loader.

The Wireless sensor technology developed and tested under this WP could be exploited in two other RFCS projects[6] and enabled the successful implementation of a 2D tracking system for vehicles and personnel with lower accuracy needs.

***Load Dependant Regulation of the Shearer***

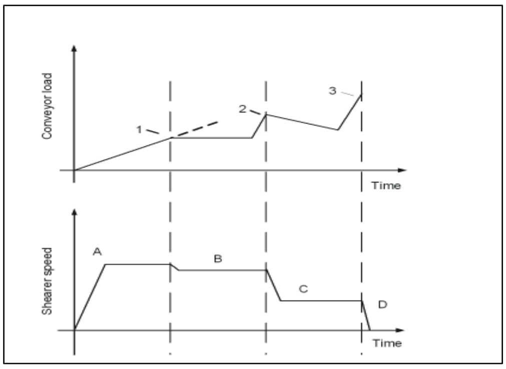
The objective is to achieve an even workload for the conveyor and to avoid stoppage caused by overloading. This is to obtain by means of a load-dependent regulation of the shearer loader speed. This requires data cooperation among the shearer and the conveyor control. The performance specifications for the shearer loader speed regulation were elaborated and the control concept developed.

[6] MINTOS (RFCR-CT-2007-00003) and EMTECH (RFCR-CT-2008 00003)

The current conveyor speed and a parameter indicating the load condition of the conveyor are required for the calculation of the reduced speed. Therefore software for controlling & communication between conveyor and shearer loader was developed. The parameters are transferred to the gate-end station.

The conveyor speed transferred and the load value is converted in the shearer loader control system to a reduction factor for the speed of the shearer loader. During operation, the speed of the shearer loader is automatically reduced. If the load condition of the conveyor exceeds an adjustable overload limit, the shearer loader speed is reduced by another 50% ***(figure 3.3.1-18)***.

In case the second adjustable overload limit is exceeded, the shearer loader is stopped




| | |
|---|---|
| **1.** | **Conveyor is at its maximum load capacity.** |
| **2.** | **Conveyor load is still increasing (roof falls, faults).** |
| **3.** | **Conveyor load reaches its maximum value (stalling).** |
| **A** | **Shearer accelerates to its maximum production capacity.** |
| **B** | **Shearer speed ireduced. The new load corresponds to the conveyed volume.** |
| **C** | **Shearer speed reduced by 50 %** |
| **D** | **Shearer stopped** |

***Figure 3.3.1-18: Load – Speed Diagram for Shearer Loader with Load dependant Speed Control***

Underground tests of the control software developed for the load dependant shearer speed regulation were successful. This overload protection system has been invented step by step in various longwalls.

***IT Level Computing Infrastructure***

In order to integrate the various complex sensing technologies into the shearer loader automation system highly sophisticated control system computing power was required. Effort was undertaken to enable IT level machine control and network integration of the machine. Consequently, the existing control systems of the shearer loader had to be extended by an IT level computing infrastructure incorporating a network of several computers, a machine server and web technologies on the machine. Thereby additional requirements arose on:

- Integration of the IT systems on the shearer into the mine's corporate networking infrastructure
- Related network security issues as the manufacturer has to maintain it's product responsibility while the machine is freely accessible inside the mine's Intranet
- Support methods for the computers and applications installed on the machine.

***Shearer Redundant Communication***

To assure a reliable communication between the shearer and the mine's central IT infrastructure, the machine server functions were extended with special networking capabilities providing multi redundant links: Wireless LAN, Fiber optic and PowerLine. ***Figure 3.3.1-19*** shows the system architecture. The shearer can use the three different network paths simultaneously or selectively. In this way even short communication interruptions can be bridged as the network traffic is transparently routed via different physical connections. Any computer in the mine's network connecting to the machine can be served by the stationary Machine Gateway computer. This computer connects to its counterpart on the machine, the Machine Server.

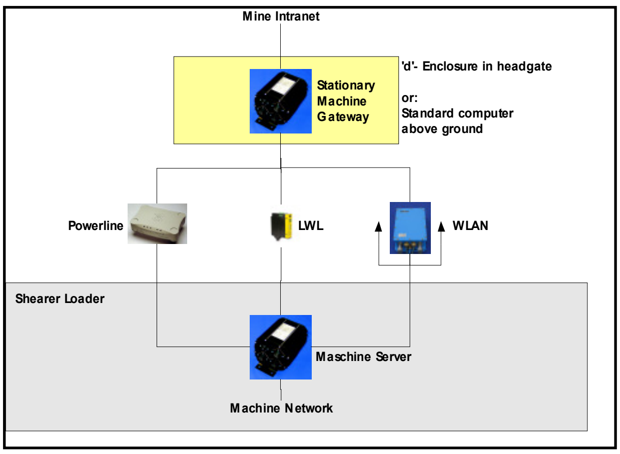



***Figure 3.3.1-19: Redundant machine to mine network setup***

***Seamless Wireless Roaming***
In order to fulfil the high demands of uninterrupted high speed communication between shearer and access points via WLAN, an improved seamless roaming was developed. With the procedure created roaming times of 2,5msec for a switchover between different access points could be achieved allowing even a disturbance free video transmission, i.e. no interruptions in digital data transmission are caused by the roaming.

***Machine Server***
For use with IT level control, an embedded machine server was developed basing on an existing platform and as a supplement to the existing real time control systems. The hardware was turned into an intrinsically safe layout and extensive software functionality was integrated to act as a web server for machine information.

The machine server is able to produce reports and online information as XML based web services which can be gathered by any permitted IT system in order to process the relevant information. Adjusting this procedure to different services of the machine is easy: It involves the definition of the related web service and the embedding of the content received from the automation software. Details of the Machine Server and machine related IT functions are given in under ***6.1.1, page 119.***

***Machine Gateway***
For network security reasons and to set up a clearly structured on board IT infrastructure the machine network functions were separated from the IT level machine control. For this purpose, an intrinsically safe networking hardware is used as a network gateway on the shearer ***(figure 3.3.1-20)***. It enables the machine server to concentrate on application functions while the separate gateway assures the secure external mine network communication.[7] Functions for machine IT integration and web based standardized data management were developed. The networking and IT devices on board the shearer are capable of seamless integration into mining network and IT infrastructures

***Figure 3.3.1-20: Intrinsically safe Machine Gateway Unit***

### 3.3.1.3 Alternative face end support systems and automatic pushing devices

The usual manual steering of the advancement of the drives and the attendant roadway equipment at the gate- end (=face end) implies that the local equipment does not follow the face advance simultaneously but often lags behind. This causes delays in face advance and leads to a wider open space at the gate-end weakening the roof stability undesirably which in turn causes downtimes. That is why automation of this process would be an important contribution to longwall automation.

As a first step an overview on face end technologies internationally in use was produced. On this basis a solution should be developed for face end automation in German collieries. The review which is

[7] The network gateway is equipped with regular copper based LAN and up to three fibre optic LAN ports. Additionally, serial interfaces and up to two WLAN transceivers are available. While acting as a WLAN gateway on the machine the unit becomes part of both the external LAN as well as of the machine internal LAN. However it securely blocks both network environments from interfering each other. To connect to automation system hardware various interface modules are available to suit different control systems of various manufacturers and to cover it by one single ATEX certification

available at the CIRCA Database led to the conclusion however that the techniques used elsewhere in the world are not applicable for German mines due to different technical and geological situations. That is why Deliverable D1.3 covers “Face End and Automation Technologies” instead of Design of automatic pushing devices for the drives”.

A basic obstacle to automation here is the necessity to dismount and remount the lining and to build a dam in the German system of double gate use. Therefore further developments focused at technologies easing these processes i.e. easy to handle lining, novel props and a face end shield avoiding the trample effect.

***Novel Roadway Lining***
Out of 4.000 potential solutions a semi circular lightweight steel or fibre-reinforced synthetic U- profile is proposed serving as a casing. The cavity is filled with concrete or synthetic material. If the side sections are of a material sliceable by the shearer no disassembling is necessary. After the passage of the face new segments are placed.

***Novel Props***
Standard roof support at the face end comprises canopy bars and wooden or hydraulic props. As an easy to handle and easy to transport alternative the idea of a 2- component foam filled prop was developed and its applicability investigated.

***Tube Design***
The foam-prop consists of a tube acting like an accordion; the reacting components cause the tube to expand vertically. ***Figure 3.3.1-21*** shows the construction. The yellow pipe starts at the bottom of the prop and ends at the upper side of the tanks in order to put the outside tube over the two tanks Through two drillings at the upper end the yellow tube the compressed air pumps the liquids through the pink tubes out of the tanks. Two blinds adjust the mixing ratio.

The blinds are sealed with a thin film which will be destroyed once the pressure reaches 4,5bar. To decrease the filling time there are two pink tubes with two static mixers. The tanks will be destroyed automatically due to the heat generated by the reaction. The air extinguishes as the outside tube is a mesh.

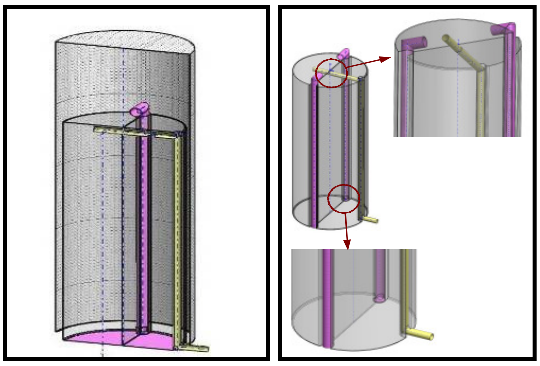


***Figure 3.3.1-21: Construction details of a foam-prop (left) and prop with outside tube***

***Foam***
In cooperation with Elastogran .as manufacturer potential products were investigated for their basic application. Various tests led to a foam with following characteristics:

- Pressure Resistance  7 MPa
- Modulus of Elasticity  400 MPa
- Density  270 kg/m³
- Core temperature  176°C; surface temperature 40°C.

The pressure resistance and the fluidic features are satisfying. The two components start to react after 2,5 minutes.

***Filter-Self-Rescuer-Test***
In order to be approved for underground use all chemicals have to pass a filter self-rescuer test. A first indication test[8] a DEKRA however had to be aborted after 5,5min due to a to high airway resistance. That is why this development could not be brought to a successful result within the project.

***Novel Self-advancing Face End Support***
In order to minimise the trample effect caused by common shields at the face end the idea of a shield with crawler tracks at the canopy and the shield base was developed. Out of various potential alternatives a shield similar to a standard model used in the face-gate-intersection in German collieries was investigated further. As a first approach a standard shield was copied with the caterpillar track replacing the usual frame ***(figure 3.3.1-22)***. Preliminary calculations were made for the construction of the caterpillar, the drive motor with sprocket, the gearing and a frame according to respective German and European standards and using FEM and SAM (**S**ynthesis and **A**nalysis of Mechanisms) for the kinematics.

With a hydrostatic compact drive by Bosch-Rexroth a drive torque of about 4 x 110.000 Nm would be obtainable - sufficient to move the shield and also to push the chain-conveyor. The necessary supporting resistance of about 300 kN/m² could be obtained with one hydraulic prop.

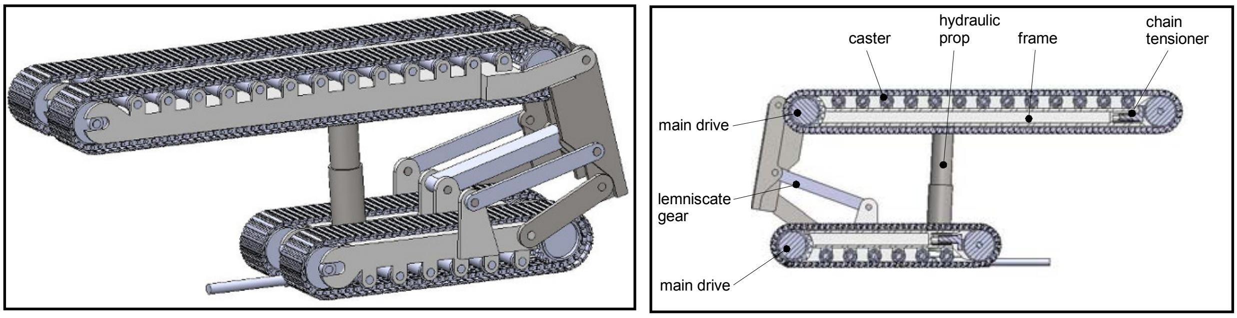



***Figure 3.3.1-22: Crawler Shield***

The calculations of other components, e.g. the lemniscates-gear, were not finished in the project, as those components are very similar to existing solutions. UoC wanted to demonstrate the feasibility of a crawler-shield only.

[8] 1/4000 of the intended amount for a 10 m face-gate intersection is burned. The smoke gases are directed through the filter-self-rescuer. The airway resistance must not exceed 5 mbar. If this test is successfully passed a further "real" test is done. Behind the filter stands a cage with rats. If they survive the test, the test is passed.

## 3.3.2 Optimisation of the cutting and loading process for Coal Shearers, Continuous Miners and Axial and Transverse Roadheaders (WP2)

### 3.3.2.1 Modelling methodology for optimisation of the cutting process

***Subtask 2.1.1 Literature Review***

A literature review was undertaken of rock fracture, rock cutting and drilling techniques in order to identify the appropriate failure mechanisms that the numerical modelling would need to simulate. The review of numerical modelling techniques applied to rock cutting was completed in order to confirm the appropriate technique to use for the numerical modelling of pick cutting (subtask 2.1.2) and led to the following findings:

***Rock Fracture and Cutting and Drilling Techniques***

The physical process of rock fragmentation under an indenter has been extensively studied in relation to rock drilling and rock boring using disk or roller type cutters. However, rock fragmentation associated with drag bit cutting has been less studied and the mechanisms consequently are still uncertain.

Almost all studies have concentrated on the effect of pushing an indenter into what is effectively a semi infinite rock surface to induce breakage, which is most relevant to drilling and disk and roller cutting. Drag bit cutting differs in that the bit travels through the rock material parallel to, and at a defined depth of cut from, a free surface-resulting in the bit repeatedly chipping to this surface and clearing its own path through the remaining rock material. The direction of penetration of the tool in relation to the adjacent free surface is therefore more favourable for breakage and we can expect the forces required for breakage to be lower. This is the case in practice, the normal and cutting forces typically being of similar values for drag bits, whilst for disk cutters the normal force is typically five to ten times higher than the rolling force.

As the chipping is less well understood there is disagreement over the roles of shear, tensile and mixed mode fracture mechanisms. Is chipping initiated from the crushed zone or from cone cracks which form before the crushed zone? Most workers have concluded that cracking occurs as a result of tensile failure. A crushed zone has been identified in front of the tip, expanding to a maximum before a major chipping event with a smaller crushed zone associated with each minor chip formation. Numerical modelling would need to simulate these observed processes to be fully realistic.

***Choice of Numerical Modelling Technique***

The aim of the modelling was to simulate in a realistic way the breakage of brittle rock by a cutting pick (drag bit type cutter) in order to identify the detailed mechanics of the cutting process, and the important rock and cutting pick parameters. In order to do this, the method must be capable of simulating the rock and bit geometry and rock material behaviour in a realistic way.

It was clear from the review that only limited studies of the drag bit cutting process had been previously undertaken and these had not been modelled realistically because studies had been confined to 2D with simple chisel picks despite the fact that simple chisels are no longer used on present day mining machines, and the ubiquitous tip shape for harder rocks is the conical shaped point attack type. The use of a 3D simulation is essential to realistically model the point attack pick.

The area of most interest was the transition between continuum and discontinuum behaviour as there was a need to investigate material behaviour at least up to the development of fractures within the rock and ideally up to and beyond the generation of a major chipping event. The review identified that the most appropriate technique was likely to be based on a continuum approach, either finite element or finite difference. Analytical methods and fracture mechanics cannot simulate the process adequately. Lattice models such as PFC, (Particle Flow Code), are not suited to modelling compressive fracture and post failure weakening, as lattice breakage means reducing the force/deformation constant to zero.

The review therefore suggested that the most likely solution at the time lay in some development of FEM, (Finite Element Method), or FDM, (Finite Difference Method), which allows realistic modelling of rock behaviour at a small scale appropriate to bit penetration in drag bit cutting, ideally in three dimensions. The main candidates based on the review were RFPA, a development of the FEM method, and FLAC a commercial finite difference package. FLAC appeared to have some important advantages:

- It is an established, commercially supported product widely used in rock mechanics applications
- Available in both 2D and 3D versions

- Realistic fracture behaviour can be simulated, based on confinement dependent element mechanical property change
- Heterogeneity in element strengths, stiffness etc can be easily simulated
- RMT already used FLAC 2D and 3D packages.

Although RFPA potentially had similar advantages (with the exception of the last), a 3D version appeared to be at a relatively early stage of development. FLAC was therefore the logical choice at this stage.

***Subtask 2.1.2 Numerical Modelling of Pick Cutting***

As indicated in the literature review the aim of the proposed modelling was to simulate in a realistic way the breakage of brittle rock by a cutting pick (drag bit type cutter) in order to identify the detailed mechanics of the cutting process, and the important rock and cutting pick parameters. In order to do this, the method must be capable of simulating the rock, bit geometry and rock material behaviour in a realistic way. Successful simulation of rock cutting would allow pick force calculations for particular rock types which could be used as input parameters for the drum design software.

An initial investigation indicated which of the pick force parameters were most appropriate to model and was followed by the development of a quasi 2D slab model. This was followed by 3D unrelieved modelling with wedge picks, unrelieved 3D modelling with conical picks and finally 3D relieved modelling scenarios. This work led to the following findings:

***Pick Force Parameters***

There are two important pick force components which are typically measured during laboratory experiments; the cutting force is the reaction to the forward movement of the pick as it moves through the rock and the normal force is the component acting at right angles to the cutting force within the central symmetry plane. The mean peak cutting force is the most appropriate parameter to target when attempting to predict force levels using numerical modelling because it relates directly to the chipping mechanism.

***Slab Cutting Simulation –Wedge Pick***

The simulation of the chipping mechanism was investigated in detail by modelling a slab of rock in contact with a wedge shaped pick. The advantages of using this quasi 2D approach are:

- there is existing laboratory experimental data for this geometry, linking pick wedge angle and rock properties with chipping force (for example Roxborough 1973)
- it gives a clear depiction of the failure behaviour of the rock as a consequence of loading from the pick contact.
- the simple geometry reduces the computing effort needed to undertake FLAC3D analysis

Simply allowing the wedge to contact the rock resulted in rotational shear failure around the wedge contact analogous to the penetration of a surface by a foundation or punch, without generating the desired chipping type failure. The explanation for this is thought to be that, no matter how fine the mesh zoning, the initial contact is effectively a single row of wedge zones along the cutting edge touching a single row of slab zones. Considerable distortion of these zones has to take place before the wedge rake face geometry comes into full contact with the slab. By this time sufficient mesh distortion at the initial contact has taken place to generate an illegal geometry error. ***Figure 3.3.2-1(a), next page*** illustrates an example of contact between the wedge and slab with generation of resulting zones of shear and tension.
In order to overcome this problem, the wedge was modelled as already being in contact with the slab over a defined length of the rake face. This is analogous to the pick "digging in" to the rock by generating small scale shear or chipping events, until the contact geometry is such that a large chipping event is generated. This process has been previously observed in laboratory testing.

A full sensitivity study was carried out to examine the relationships between the model parameters, the mode of failure and the calculated force level. This is reported under subtask 2.1.3.

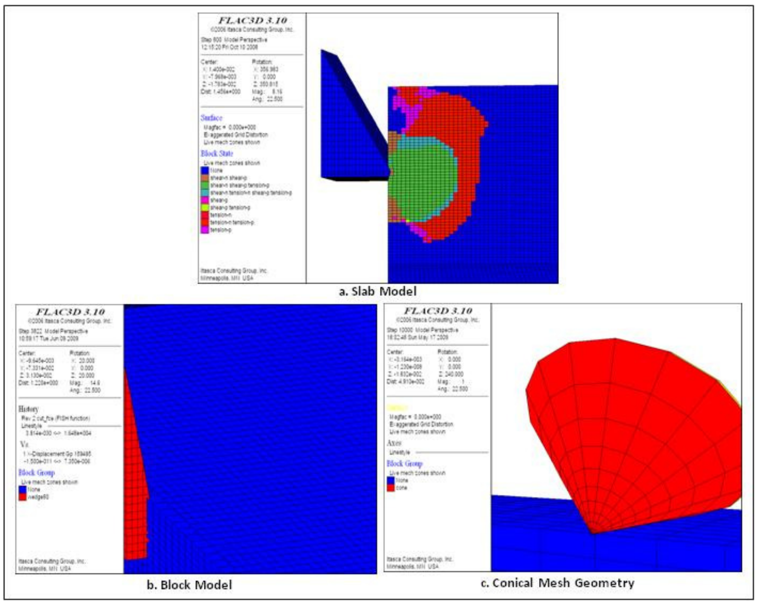



***Figure 3.3.2-1: Mesh Geometries for Slab, Block and Conical Pick Geometries in FLAC3D***

***Three Dimensional Block Cutting Simulation with Wedge Picks***

Experimental data exists for wedge picks cutting in both unrelieved (isolated cuts) and relieved mode in a range of rock types. The majority of the parameters established during the slab simulation runs were retained for the block simulation, including a pick penetration depth of 2.5 or 5 mm. The width of wedge pick is an additional potential variable in this case. The increased lateral dimensions of the model resulted in a much larger number of zones, and graded zoning was used to allow sufficient zone density close to the pick while maintaining acceptable run times of less than 24 hours, ***figure 3.3.2-1(b).***

When a pick cuts adjacent to a previously excavated cutting track, the chip failure will extend towards the existing cut. Below a certain cut spacing to depth ratio, the rock ridge or “land” between them will break off. This results in efficient cutting, because the volume of material removed is maximised for little or no increase in force levels. Experimental data for wedge picks in this cutting situation are included in several studies. To simulate this geometry, the unrelieved model block was extended laterally and a cutting groove, of the same cutting depth, incorporated at chosen spacings from the wedge pick. The cross sectional geometry of the groove was chosen based on the results of unrelieved cutting tests. Initial proving runs established that the shear bulb extended towards an existing cut, even where failure did not remove the kerf, and the cutting force reduced compared with the unrelieved value when the failure extended laterally to the nearby cut. Detailed comparison of experimental data and model predictions are described under subtask 2.1.3 (see below).

***Simulation of Rock Cutting with Point Attack (Conical) Picks***

The simulation of the conical pick geometry using FLAC3D was much more difficult than for wedge shaped picks. This is because the available FLAC3D primitive mesh shapes do not include a cone or any curved shape which could be adapted to form a cone. Consequently it was necessary to form a segmented cone using tetrahedral mesh elements, ***figure 3.3.2-1(c).*** The wedge pick studies suggested that it was necessary to embed the pick in the rock to obtain realistic results and, for a conical shape, this presented further geometric difficulties. These were overcome by developing procedures using a combination of FLAC and FISH routines to generate the conical pick and embed it in the rock to the chosen depth of penetration and angle of attack. Using these procedures for an embedded cone it proved possible to reproduce the essential shear chipping type failure characteristically seen with wedge picks with increase of cutting force to a maximum at which shear failure occurs to the top block surface. Results are described under subtask 2.1.3.

***Subtask 2.1.3 Validation/Improving of the Numerical Modelling***

The work started with sensitivity studies for the quasi 2D model slab to determine correct modelling parameters to obtain realist results when compared to experimental results. Studies were then conducted for the 3D modelling unrelieved with wedge picks, 3D relieved with wedge picks and 3D unrelieved with conical picks.

***Slab Cutting Parameter Sensitivity Study***

The quasi 2D slab model was used to investigate the effect on calculated cutting force and rock failure pattern of the applied wedge velocity, interface properties, initial contact area, mesh density, depth of cut, rock properties and wedge angle. The results are summarised below.

***Velocity***

Results were found to be sensitive to the applied velocity if the resulting shock generated an initial force level exceeding about 10% of the final maximum force. The initial force was found to be directly proportional to the velocity applied and also depended on the model geometry (size of contact area) and zone density, with smaller zones giving a larger initial force. The results allowed determination that in general a velocity of 1e-9 or less was appropriate to subsequent modelling.

***Interface Properties***

Interface properties at the pick rock contact include interface cohesion, tension and friction. Cohesion and tension were set to zero, the interface being considered to have zero bond strength and be purely frictional in nature. A sensitivity study of interface friction angles between 0 and 60 degrees confirmed that, although there were corresponding changes in the pattern of early failure in the vicinity of the wedge, the resulting effect on the calculated peak cutting force was small. Sliding friction between tungsten carbide and rock has been determined in the past, Roxborogh and Phillips (1975), as around 30 degrees and this value was used in later models.

***Depth of Penetration (Degree of Embedment)***

Pre-existing contact of part of the pick rake face with the rock was found to be necessary to obtain realistic rock deformation and failure patterns. A penetration of around 5mm or less with 25mm depth of cut was found to give realistic chipping type failure patterns and was adopted as standard.

***Mode of Failure***

When chipping type failure was successfully reproduced in FLAC3D models with embedded wedge picks, the failure mode indicated was dominated by shearing. With low tensile strength parameters it was found that tensile failure resulted in general splitting or disintegration of the test slab rather than the curved chipping failure surface illustrated in publications. As FLAC3D is a package built around the observed shear behaviour of rock and soil materials it is perhaps no surprise that the shear failure mode is successful in replicating the observed rock failure pattern in this case. The switch towards shear failure with greater wedge/rock contact and greater precision both suggest that it is appropriate to look for shear rather than tensile failure as the means for predicting cutting force when using FLAC3D. Consequently the tensile strength was set equal to the cohesion for the rest of the slab study. This ensured that shear failure was successfully simulated in all cases to give a valid comparison.

***Effect of Cohesion and Angle of Friction***

Runs were made using an angle of friction of 20, 30 and 40 degrees. In all cases the results exhibited the expected shear failure pattern. The cohesion is the rock strength parameter which most strongly influences the maximum cutting force, with a near linear relation over the tested range. The angle of friction within the expected range also influenced the force level, but to a lesser extent.

***Effect of Wedge Angle***

To investigate the effect of wedge angle, the slab simulation was used with wedge angles from 60 degrees (30 degrees positive rake) to 110 degrees (20 degrees negative rake) and the resulting cutting force and mode of failure evaluated for a range of penetration depths, at widths of cut of 25.4mm and 12.7mm. The results are shown in ***figures 3.3.2-2(a) and (b), next page.*** The best data fit with the chosen parameters was with pick penetrations of 2.5mm or 5mm.

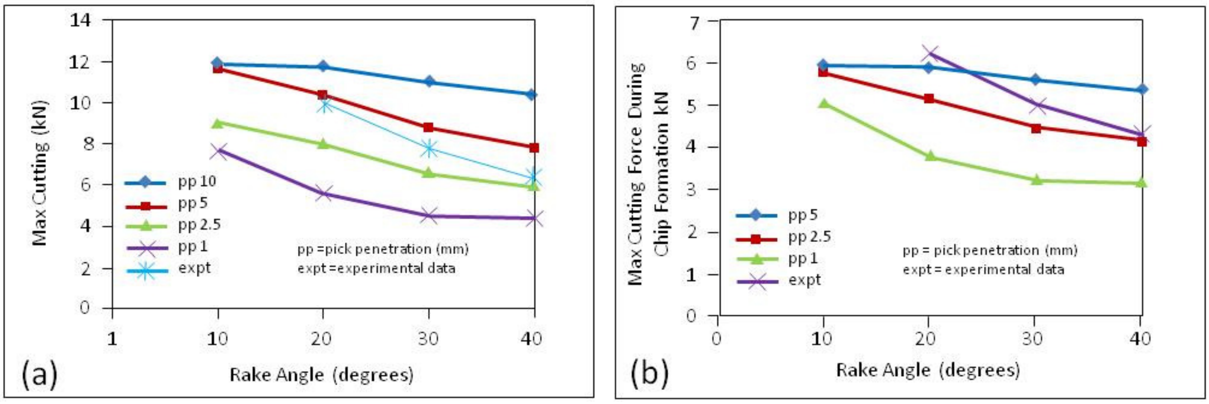



*Figure 3.3.2-2: Maximum Predicted Cutting Force for Chip Formation versus Wedge Rake Angle; (a) 25.4mm width of cut, and (b) 12.7mm width of cut*

***Comparison with Test Results for 3D Unrelieved Cutting with Wedge Picks***

For the 3D situation initial runs were undertaken with a 25.4mm wide, 60 degree wedge at 5mm penetration to compare results with the slab model. Failure again occurred predominantly in shear both ahead and laterally with the peak cutting force coinciding with failure of a chip with a forward shear angle of about 30 degrees from the horizontal. Lateral breakout was steeper at about 45 degrees**, *figure 3.3.2-3.***

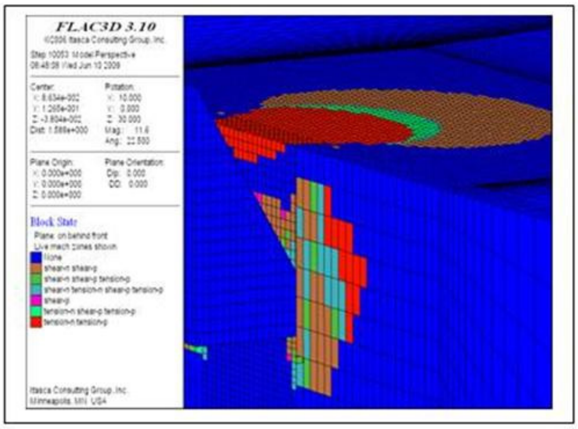



*Figure 3.3.2-3: Chip Formation – 3D Block*

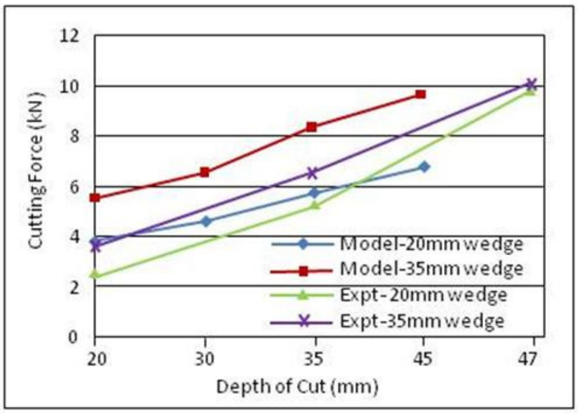



*Figure 3.3.2-4: Comparison of Model and Experimental Results for 3D Unrelieved Cuts in Chalk*

***Simulation of 3D unrelieved cuts in chalk with wedge picks***

Comprehensive laboratory cutting and mechanical strength tests in chalk have been reported by Roxborough and Rispin (1972). The data includes unrelieved cutting tests for 30 degree rake (60 degree wedge angle) picks with widths of 20mm and 35mm. The experimental results were variable due to chalk property variability. However within this constraint, agreement with the model results was good, the model results providing a consistent picture, ***figure 3.3.2-4*** above.

***Simulation of 3D unrelieved cuts in Bunter sandstone with wedge picks***

A study of mechanical cutting, with associated strength data, in Bunter sandstone, includes unrelieved cutting tests for 0- 30 degree rake (60-90 degree wedge angle) picks for a range of pick widths and cutting depths, Roxborough and Phillips (1975). ***Figure 3.3.2-5(a), next page)*** compares experimental results with the computer predictions for a 30mm wide wedge over the range of cutting depths and ***Figure 3.3.2-5(b), next page*** plots the cutting force against wedge width at the average cutting depth of

9mm. Both comparisons exhibit good agreement between the model and experimental results. For the wedge width results a positive intercept at zero depth is implied in both cases. This represents the force needed to excavate a ‘V’ shaped groove at zero wedge width.

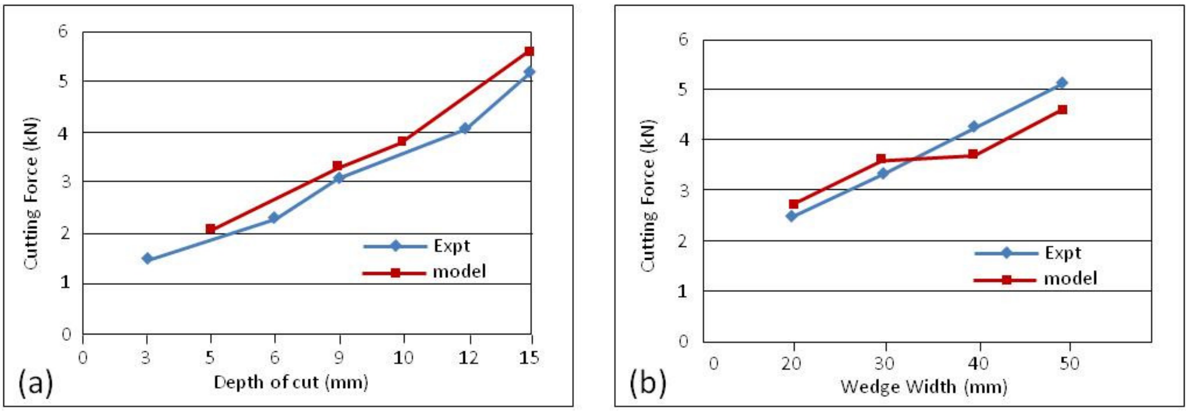



*Figure 3.3.2-5: Maximum predicted cutting force for chip formation for bunter sandstone (a) for depth of cut (80° 30mm wide wedge) and (b) for wedge width (80° wedge 9mm depth)*

***3D Relieved Cutting with Wedge Picks***

***Simulation of 3D Relieved Cuts in Bunter Sandstone with Wedge Picks***
Experimental data for relieved cutting in Bunter sandstone is included in Roxborogh and Phillips (1975). The data includes relieved cutting tests for 0-30 degree rake angle picks with widths of 20mm to 50mm at a range of depths of cut. The unrelieved simulation gave accurate cutting forces with a cohesion of 1.5MPa and a friction angle of 25 degrees and these values were retained for modelling relieved cuts.

A higher precision mesh was specifically developed to ensure that the existing cut profile could be accurately simulated with a 30 degree breakout angle. The results showed a reduction in the unrelieved cutting force value as the spacing reduced below 70mm. The agreement between model and measured force values was extremely close.

***3D Unrelieved Cutting with Conical Picks***
The conical pick model was used to simulate unrelieved rock cutting at 25mm depth using the same rock parameters as for the 60 degree wedge pick. With a cone maximum diameter of 25mm, the resulting maximum cutting force with 5mm embedment was similar to that obtained with wedge picks using the same rock parameters. Shear failure to the block upper surface occurred in the same way, with a curved shear surface for depths of penetration of 2.5mm or more. At zero penetration, in contrast, only one cone segment surface contacted the rock block, and the results were again analogous to those obtained for penetration of a punch.

The numerical modelling described in the above sections was used to produce Deliverable 2.1 ***“Methodology to analyse the failure mechanism of rock under mechanical tools”*** which leads to improved knowledge of the rock cutting process, particularly an understanding of tool-rock interaction. Hence optimized cutting techniques for coal and coal measure extraction identified.

### 3.3.2.2 Software Development for Drum Design

***Subtask 2.2.1 Literature Review and Database***
A literature review was undertaken in order to ascertain the types of drilling and cutting machines currently in use worldwide that the software would need to accommodate. According to this review excavation machinery utilising tungsten carbide tipped drag bits (picks) is ubiquitous in coal mining

worldwide. The most widespread coal mining machines are longwall shearer loaders and for room and pillar operations, continuous miners. Roadheaders, either transverse or axial, are sometimes used for development, mainly in Europe and particularly when out of seam. The main trends in recent years have been in the increasing power of these machines and development of more sophisticated control technology.

The key to further development in cutting technology appears to lie in new materials technology for the cutting tips, namely PCD, Polycrystalline diamond composites. In mining their use on pick tips is being actively researched to overcome the problem of premature failure. The drag bits used today are virtually identical in form to those in use in the 1980s. Conical picks are the most common, used worldwide on shearers, roadheaders and continuous miners. Radial wedge type picks are now largely restricted to longwall shearer drums, mostly in the UK with some installations in the USA and elsewhere.

Laboratory studies of rock cutting have been undertaken recently in the USA, Australia and Turkey. These have been used to correlate rock properties with pick forces, to study dust make and cutter wear and to simulate the interaction of picks on rotary machines. Field tests with shearer drums have been carried out in Australia and with roadheader cutting heads in the UK and Turkey in order to investigate the relation between individual pick forces and rotary drum reaction forces and torque. The results provide a very high level of validation of the original concepts developed by MRDE and incorporated in the computer design programs. The general design concepts have been shown to be valid and the balance calculation accurate.

***Database of Cutting Drums***
It was anticipated that a range of modern cutting drum designs would be obtained. This would allow qualitative information for the literature review above but also provide data for quantitative analysis by the cutting drum software under development as part of the project. The information obtained is contained within a database and forms *Deliverable 2.2*.

As indicated in chapter 3.2.2 it proved to be very difficult to obtain a good number of current drum designs. These drum designs are often referred to as the ‘lacing diagrams’ and contain all the relevant data to allow 3D representation of the drum and cutting tools, and a performance analysis using suitable CAD software. The strategy for data collation was to approach both drum manufacturers and coal mines to request drum design data. The response of companies and mines to requests for information was beyond the control of RMT.
The main problem was that the drum lacing designs were seen by the drum manufacturers/suppliers as their design copyright which gives them a perceived design advantage over their competitors. Consequently the coal mines in most cases did not necessarily receive any details of the drum lacing designs and as such had limited quality control over the products supplied by the manufacturers.

Deliverable 2.2 is less comprehensive than anticipated but does contain examples of all drum types, (shearer, continuous miner, axial roadheader and transverse roadheader). However, importantly, sufficient data was obtained for software development, subtask 2.2.2, and analysis in chapter 3.3.2.3.

***Subtask 2.2.2 Determination of requirements and software development***
The aim was to develop an initial working version of the software, based on the determined requirements, to provide a tool for drum design analysis during the early stages of the project. This was then further developed and refined during the course of the project as part of chapter 3.3.2.3.

The major improvement required over the programme used in the 1980’s by British Coal was that the new software needed to allow for analysis of continuous miner drums and transverse roadheader drums both of which were not in common use in the 1980’s, (the British Coal software concentrated on shearer drums and axial roadheaders). The new software needed to allow the input of multiple drums as used on continuous miners and allow analysis of the breakout patterns at the intersections between the drums. It also needed to be able to accommodate both the sumping and slewing modes of cut used by roadheaders. Specific recommendations were also made with respect to the input options, 3D visualisation, breakout pattern generation and force balance calculations and presentation.

The initial working version of the software developed was able to undertake analysis for all 4 machine types but was not initially developed to be capable of analysing the Sumping action of an axial roadheader and the Slewing action of a transverse roadheader. This was addressed in the software revision of Task 2.3 (chapter 3.3.2.3.), along with other revisions.

***Figure 3.3.2-6, next page*** shows the 3D visualisation in the software using a continuous miner cutting drum as generated by the initial working version of the software. The left hand diagram is a front view of the picks arranged on a continuous miner drum, (comprising three drums), with both the visible picks on the front and the picks that would be hidden by the drum shells. The top right part shows the side view of the pick distribution around the drum shell. This stage of the analysis allows for identification of pick box interference and feasibility of manufacture.

***Figure 3.3.2-7, next page*** shows the breakout pattern to assess the pick cutting duties by diagrammatically displaying the area of material removed by each pick as the drums rotates and advances into the material. The area bordered by the breakout lines represents the amount of material taken by each pick and with correct interpretation indicates which picks are overloaded or under utilised.

The probability of excessive machine vibration is analysed by computing the forces produced by the drum as it cuts through one revolution. An example of the force balances generated is given in ***figure 3.3.2-8***, ***page 44.***

### 3.3.2.3 Analysis of Current Drum Designs by the New Software and Software Revision

Both the analysis of current drum designs and software revision operated concurrently. It is logical to describe the software revision first then the analysis of current drum designs.

***Software Revision***
As indicated before a working version of the revised software was written in order to produce a tool for undertaking drum analysis on continuous miners and transverse roadheaders as well as the shearers and axial roadheaders which could be analysed by the now obsolete and unusable 1980s British Coal software. Pick design has changed little since this time so no major refinements were required to the software in this respect. Installed machine power has increased significantly since the 1980's and the initial working version of the software accommodated for this through a wide range of advance rates per revolution.

The initial working version of the software thus, by analysing case studies from the database, satisfied the majority of the refinements required due to machinery changes since this time. However it did not incorporate the capability of analysing the Sumping action of an axial roadheader and the Slewing action of a transverse roadheader. This was achieved under software revision along with the writing of the software in a more future proof programming language, with significantly improved 3D graphics.

***Main Results***
The challenge was to identify and develop a more robust software package using a computer language that could be used on a wide range of today's computer hardware. Microsoft's .Net2.0 was selected for this.

The 3D representation of the cutting drums in Microsoft's .Net 2.0 computing language was fairly easily achieved and is illustrated in ***figure 3.3.2-6, next page*** as compared the original presentation.

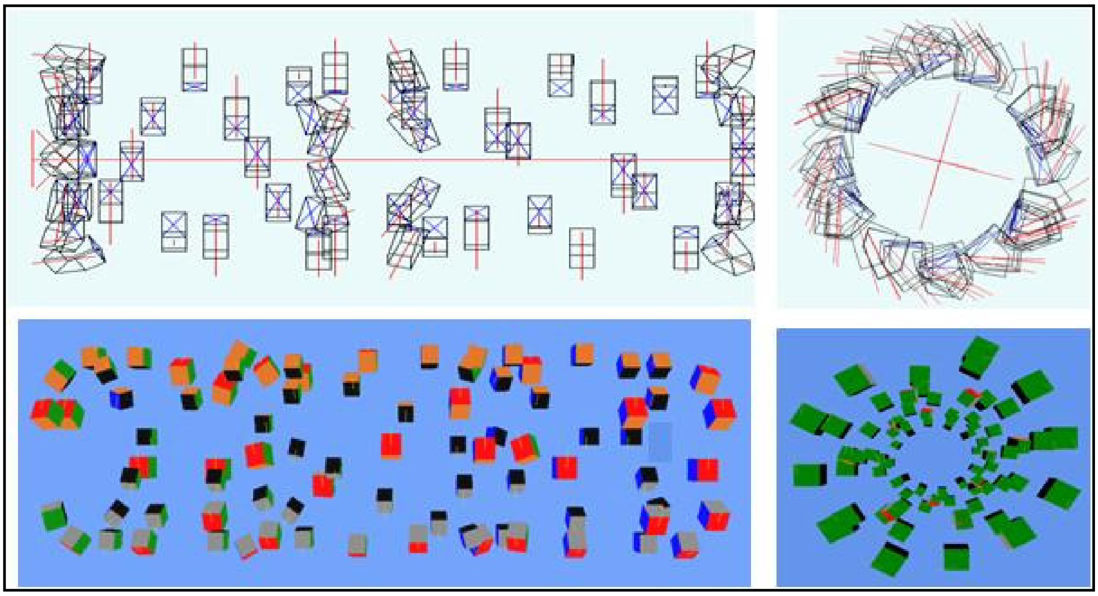


***Figure 3.3.2-6: Original and New True 3D Visualisation of a Cutting Drum (Continuous Miner) following Software Revision***

Whilst creating the breakout pattern many obstacles were encountered due to the complexities of the geometries generated, (illustrated in ***figure 3.3.2-7***), and methodologies available in the alternative programming language. However these were overcome. The breakout pattern and resultant force analysis for the Sumping action of an axial roadheader and the Slewing action of a transverse roadheader was also incorporated.

After finalising the breakout pattern analysis, the appropriate code was written in order to generate the appropriate cutting force graphs as shown in ***figure 3.3.2-8, next page***. These can also be accompanied by cutting forces statistics to show the minimum, maximum, mean and standard deviation for each series on the graph.

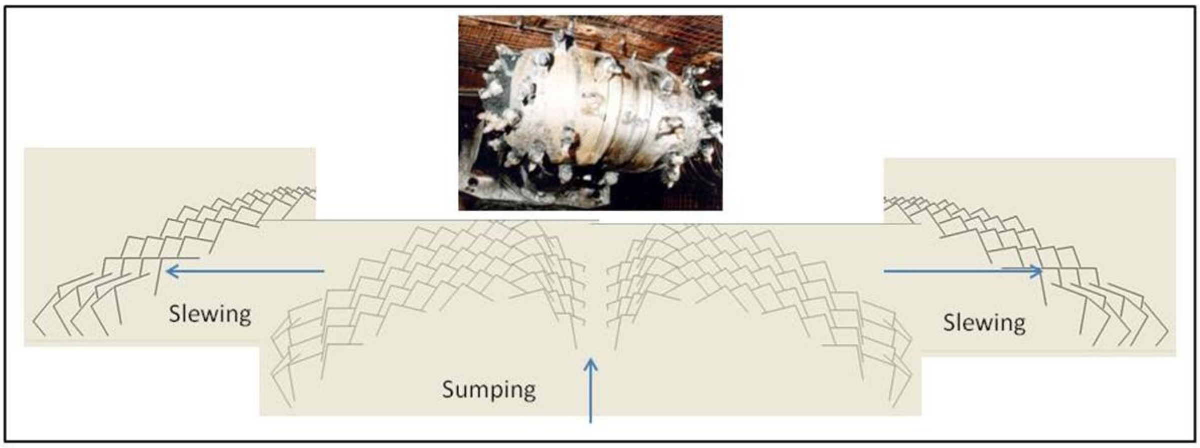



***Figure 3.3.2-7: Slewing and Sumping Breakouts from a Transverse Roadheader***

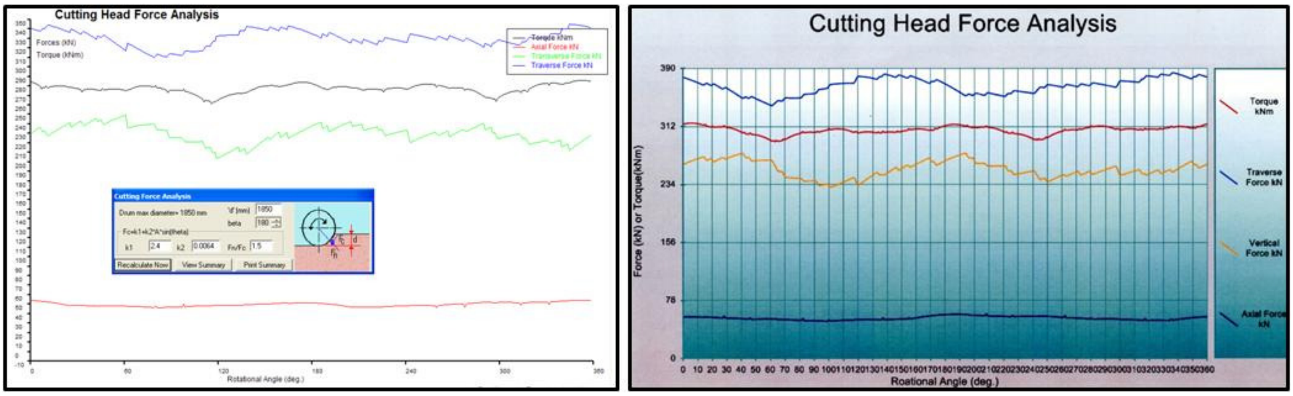



*Figure 3.3.2-8: Old and New Cutting Head Force Analysis Graphs*

Once all the major features had been created within the software it was fully tested for 'bugs' and a comprehensive help file created and compiled. The minimum PC specification for the software is a screen resolution of 1024 x 768, 2GHz processor, 512mb RAM and a Directx9 compatible graphics card.

***Analysis of Current Drum Designs***

One of the reasons for the analysis of current drum designs using the new software was to determine where refinement of the software developed in task 2.2 (chapter 3.3.2.2) was required. This software revision as part of task 2.3 (chapter 3.3.2.3) has already been described above. Analysis of current drums was also undertaken with a view to using the new software and combining it with other design tools in order to develop a drum design review strategy for the optimisation of drum design. The developed strategy and the results are described below.

The software developed can be used 'stand alone' to design a cutting drum from scratch by arranging the picks in suitable vane and lines spacing geometries around the drum to achieve optimal cutting conditions, or it can be used as part of an iterative process in order to determine the cause of the poor performance of a current drum design in operation.

Optimisation of a cutting drum deployed underground is required where one or more of the following is observed: high pick consumption, reduced cutting rates due to worn/damaged picks, damaged and failed pick boxes, down time in replacing picks, premature repair and/or replacement of drums or premature failure of drum gear boxes and motors. The causes could be faulty picks, (poor metallurgy and/or manufacture), poor drum design and/or manufacture, or exceptionally hard cutting conditions.

The solution is to design the cutting drums to suit the prevailing conditions using the best available picks and boxes. The approach has been to develop an independent assessment of the cutting efficiency of existing drums and to optimise their performance, whilst avoiding proprietary clashes between pick, drum and machine suppliers. The following approach was developed during NEMEAQ with specific steps also developed under the project as indicated:

Stage 1

- Perceived problem
- Pick consumption surveys (methodology specifically developed under NEMEAQ)
- Rock property tests on the coal and any stone bands cut
- Rock property data from numerical modelling (methodology specifically developed under NEMEAQ)
- Metallurgical tests of the picks
- Thermal imaging of the drum
- CAD analysis of the drum design (software specifically developed under NEMEAQ)

Stage 2

- Drum re-design/optimisation using CAD analysis (software specifically developed under NEMEAQ)

Stage 3

- Further pick consumption and thermal imaging surveys to confirm improved performance

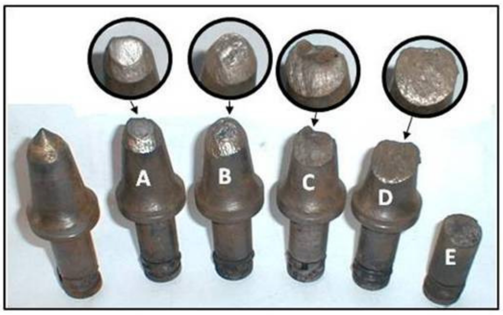
In an ideal situation the tools developed within this project would have been applied to a single case study through all 3 stages outlined above. This has not been possible for logistical reasons, i.e. some of these tools were only finalised toward the end of the project and the non-availability of appropriate field sites and manufacturers' design drawings. However through the data collected and analysis of site specific data it is possible to demonstrate the philosophy using one of the field sites with a minor amount of supplementary information from other sites.

***Perceived Problem***

In the continuous miner field study exemplified here an inspection of the machine indicated that cutting conditions did not appear difficult and machine vibration during the cutting cycle was not excessive. However the breaker picks mounted at the drum intersections did not appear effective in removing the ribs left between the drums which led to problems when sumping. Although a range of pick types were used of varying reach and shank size, most picks were found to be free to rotate in their boxes and worn symmetrically on the main body of the drums. However the picks forming the outer clearance rings and drum intersections were found to be asymmetrically worn. In extreme cases the tungsten carbide inserts had been exposed along their full length indicating excessive abrasive wear.

***Pick Replacement Surveys***

The wear pattern and condition of used and broken picks gives information on cutting conditions, pick failure modes and pick manufacturing defects. Rapid wear or repeated failure in particular positions can identify a problem with the drum design or manufacture. A simple pick replacement survey system was developed that could be completed by the machine operators to identify the type of pick failure and its location for detailed analysis. Based on field studies the examination of picks replaced during routine maintenance of the cutting drums it was found that the pick wear could be divided into five groups as illustrated in ***figure 3.3.2-9*** below.




A - Even wear of the carbide (picks rotating freely)
B - Carbide fractured leading to rapid wear of the pick
C - Uneven wear of the pick body leading to the carbide being washed/plucked from the pick body. (picks incorrectly positioned)
D - Loss of carbide, just stump of pick body remaining indicating rapid wear between pick inspections
E – Lost pick or failed sleeve

***Figure 3.3.2-9: Photograph to illustrate the types of pick wear that can be observed during a pick replacement survey***

To investigate the relationship between the type of pick wear and their location on the cutting drums a system of recording the picks replaced during a production shift was devised following discussions with the machine operators and underground mine district managers. This comprised a booking sheet, which divided the 3 drums into 7 cutting zones as indicated in ***figure 3.3.2-10(a), next page.***

At the field site such pick replacement surveys were undertaken and confirmed the visual observations. Pick wear could occur rapidly between inspections and was concentrated in the 'corner' cutting zones at the outer clearance ring and drum intersections. Typical wear rates could be as much as 4:1 between the 'corner' cutting picks and those positioned on the body of the drum. ***Figure 3.3.2-10(b)****, next page* shows some typical results from over a number of shifts for a 4 month period. The average pick performance was 69 tonnes/pick.

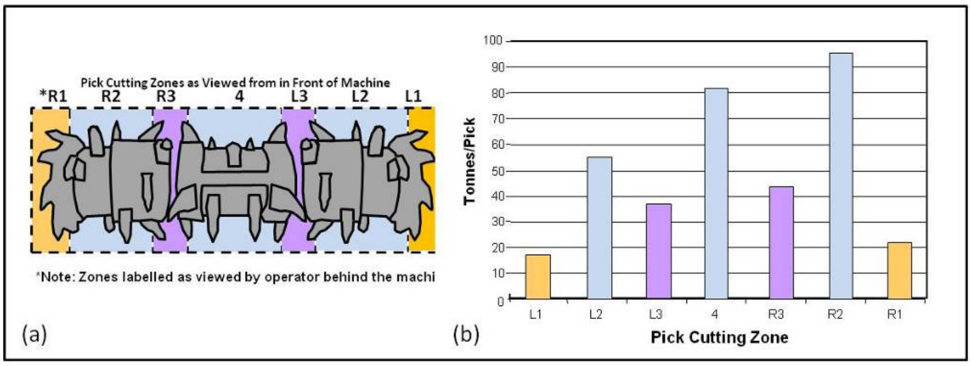



***Figure 3.3.2-10(a): pick location identification system for worn picks on continuous miner drums, (b) pick replacement survey results showing increased wear (decreased tonnes/pick) for the kerf (orange) and intersection (purple) picks***

***Metallurgical Examination***

The purpose of this type of examination is to establish if the picks were made to specification, and if so, if the grade was suitable for the cutting conditions. Metallurgical examination of selected picks at the field site found them to be within the manufacturers' specifications. This grade was specified in the manufacturer's data sheets as a low wear, high impact grade and as such may not have been the most suitable for the present conditions where the picks were excessively worn by abrasion and did not appear to be suffering from major impact loading. The most likely cause would be the presence of sand / grit stones within the coal seam and it was recommended that this be investigated further by measuring their abrasivity.

***Rock Property Testing***

Rock property testing can be used to determine the cuttability, strength and abrasivity of the coal and any stone bands cut. The cuttability test can be used to determine the machine power required while strength and particularly abrasivity can be used to assess whether excessive pick wear could be attributable to the rock properties.

***Cuttability (Specific Energy) Testing***

The instrumented cutting test, (McFeat-Smith & Fowell 1979, Fowell *et.al.* 1994), takes account of the rock strength and toughness by measuring force acting on a full scale tool during an instrumented cut. From the mean cutting force and the volume of material excavated the specific energy can be determined for the cutting conditions employed. Specific energy is a variable dependant on depth of cut, tool geometry and spacing between tools. Provided these are kept constant, the specific energy obtained is a measure of the cuttability of a rock material. The results from the grooving test can allow prediction of cutting performance and identification of cutting problems for a range of cutting machines. As a general guide to relate laboratory specific energy to the cutting performance of roadheading machines the results of McFeat Smith & Fowell, (1979), can be used.

Within this project a set of Specific Energy tests were undertaken for a UK colliery in order to assist with the choice of axial roadheading machine in terms of power. For the strongest sandstone within the cutting horizon a specific energy of 7.8MJ/m3 was recorded which indicated, along with UCS, Uniaxial Compressive Strength and abrasivity test results, that a medium weight machine would be more than capable of cutting strata predicted to be encountered. ***Figure 3.3.2-11*** shows a photograph of the instrumented cutting test.

***Figure 3.3.2-11: photograph of an instrumented cutting test***

*CERCHAR Abrasivity*
The CERCHAR test, (West 1989), is widely accepted as a test for measuring the abrasivity of rocks in the mining and civil engineering industries.  The abrasivity number is determined by dragging a steel stylus across the specimen under a load of 7kgf.  The dimensions of the wear flat produced on the stylus is used to produce the CERCHAR index number expressed in tenths of a millimetre (i.e. 0.1mm = 1 on the CERCHAR index).  The class divisions suggested by CERCHAR  range from 0.3-0.5 being not very abrasive to 4.0-6.0 being extremely abrasive.

At the field site the CERCHAR abrasivity for the ‘A’ seam coal was 0.09-0.11, and the ‘A’ Seam stone band 0.57-1.16, and for the ‘B’Seam 0.14-0.16 for the coal and 0.52-0.86 for the stone band. These results indicate that both the coals tested were considered to be non abrasive on the CERCHAR index whilst the sandstone rated as slightly to medium abrasive.  This would suggest that the tungsten carbide tips used at the time were too soft considering the excessive wear rates experienced during the cutting cycle.

*UCS Testing*
At the field site the UCS tests confirmed that one of the two coal seams was significantly stronger than the other, giving values of 55 MPa  and 32 MPa respectively. The UCS test of sandstone samples taken from both seams indicated similar UCS values of 100 MPa. In rock cutting terms this was not considered to be a particularly difficult cutting proposition when banded, particularly as it had a low abrasivity index.

*Rock Property Data from Numerical Modelling*
Using the numerical modelling developed in Task 2.1 (chapter 3.3.2.1) it was demonstrated that the cutting force required for chip formation could be accurately predicted using the cohesion and angle of friction.  This could therefore replace the cuttability test where the triaxial properties of the rock are known. Even where the triaxial properties are not known, triaxial testing is more readily available than cutability testing and is more cost effective.

***Deliverable 2.1*** provides the methodology for analysis of the rock failure mechanism under machine tools and indicates that the numerical modelling has the potential to replace the expensive cuttability test, (where triaxial rock properties are known), and to quantify pick forces and specific energy for realistic cutting geometries thus making a significant advance compared with conventional laboratory testing.

*Thermal Imaging for the Analysis of Current Drum Designs*
As part of the process of evaluating current drum designs where optimisation of the drum design may be required RMT investigated the use of a thermal imaging camera.  This has been used to record pick wear patterns on drums based on the assumption that harder working picks are hotter.

The Fluke Ti 25 thermal imaging camera was selected as being the most appropriate ‘off the shelf’ instrument at the time.  As an ‘off the shelf’ instrument’  its use is limited as it is not intrinsically safe for use in coal mines and therefore has to be used under managers rules for scientific instrumentation. ***figure 4.3.2-12*** shows thermal images of picks on a continuous miner.  These images confirm that the camera can be used to analyse a drum for picks running hotter and working harder.

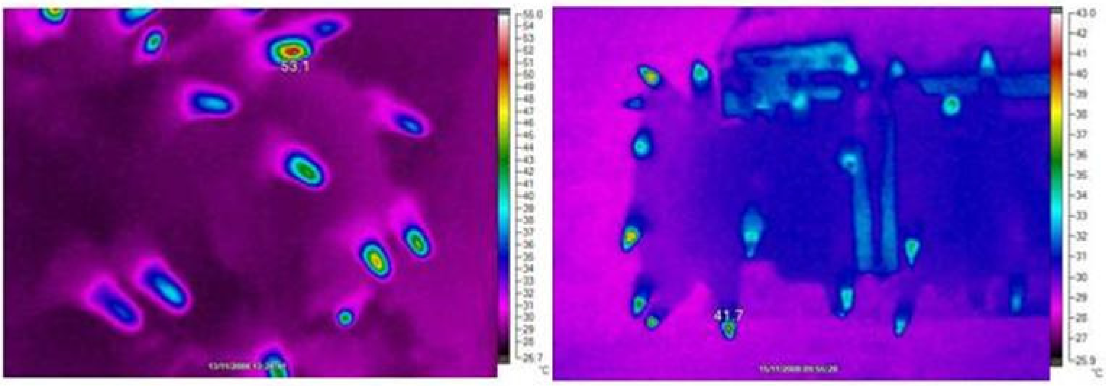



***Figure 3.3.2-12: thermal image of a continuous miner drum illustrating the higher temperatures of the kerf picks***

***CAD Analysis of Drum Design***
Analysis using the new software for the field site indicated shortcomings with the designs of the outer clearance rings and intersections with uneven distribution of the pick duties. ***Figure 3.3.2-13(a)*** shows the break out patterns for the outer drum and the inner drum and indicates where picks are cutting with their sides, which would explain the asymmetrically worn picks found in these areas.

The force balance graph is shown in ***figure 3.3.2-14(a)*** and this shows relatively high fluctuations in the cutting forces as would be expected for a poor drum design**.**

***Drum Re-design/Optimisation Using CAD Analysis***
Using the CAD software an alternative design for the above continuous miner drum was proposed. ***figure 3.3.2-13(b),*** shows the breakout pattern of this design which was developed to produce a more even distribution of the pick cutting duties at the drum intersections and end kerfs. The force balance graph is shown in ***figure 3.3.2-14(b),*** and shows significantly reduced fluctuations in the cutting forces.

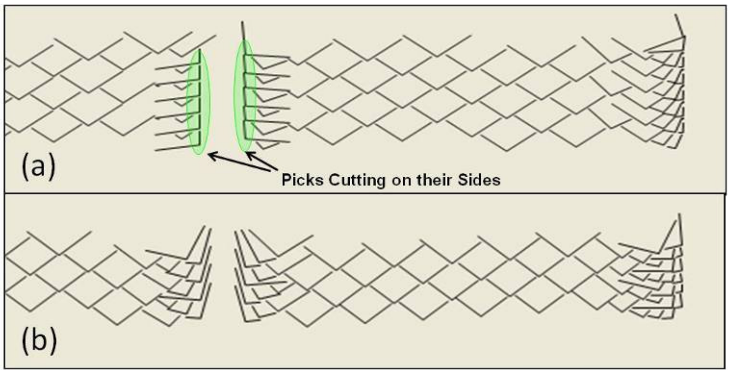



***Figure 3.3.2-13: Breakout Patterns from LH Drum and Centre Drums of the Continuous Miner Drums at the Field Site***

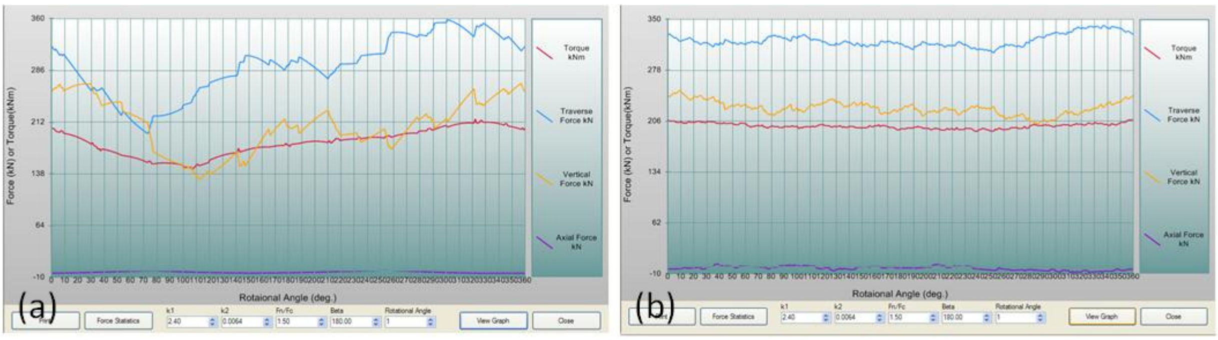



***Figure 3.3.2-14: Force Balances for the Whole Cutting Drum of the Continuous Miner at the Field Site***

***Further Pick Consumption and Thermal Imaging Surveys to Confirm Improved Performance***
Following a proposed redesign it is then logical, if the new design is deployed, to conduct further pick consumption surveys and thermal imaging in order to determine the level of improvement in cutting performance; and to determine if further improvements are required.

In the field study site described here, the proposed drum design was commissioned, deployed underground and further pick consumption surveys were undertaken. The improvement in pick performance in terms of tonnes cut per pick, increased from 69 to 500 tonnes per pick. In addition to the measured improved pick life it was reported by the machine operators that the machine vibration had been reduced considerably. Initial vibration analysis had confirmed this although further investigation was required.

The only reported disadvantage of the re-designed drum was that at the increased depth of sump required to optimise the loading of future larger shuttle cars the cutting rates were reduced. This was caused by the projection of a coal core between the drum intersections and poor initial design of the core breakers supplied. A drum design revision was therefore recommended.

In summary good drum lacing design can be achieved using the methodology and CAD design software developed under the Project, but in order to take advantage of these improvements, accuracy during manufacture must be carefully controlled. Acceptable tolerances are +/-2mm on pick position and +/-2$^{o}$ on angular position. If these are not achieved, poor cutting performance and excessive machine vibration may result. The introduction of such inspections in British Coal in the 1980's lead to an initial rejection rate of up to 50% of all drums delivered to site.

### 3.3.2.4 Results Dissemination

Golder RMT has a network of connections within the industry and clients alerted to the improved capability. Currently Golder RMT, are advising a European client on the cuttability of roof and floor rock for a new mining prospect with a seam thickness of 1-2.2m. A range of rock properties have been determined including cuttability.

If a longwall shearer is used some roof and floor rock will need to be cut by it, and drivage machines will need to excavate gate roads at least 2.5m high. Current advice is centred on suitable machines and pick types. Later work may include specific designs for rock cutting. An abstract has been written for submission for a Conference for dissemination to a wider audience. This could not be completed before project completion as significant parts of the work continued up until the completion of the project in June 2009. It is planned to submit and publish in 2011, see chapter 2.2.4.

## 3.3.3 New methods for monitoring/diagnostic of machine operations/ conditions, maintenance and maintainability (WP3)

### 3.3.3.1 Development of monitoring and visualisation of machinery systems operations and machinery contamination control

A comprehensive visualization system designed to present the operational parameters of a mechanized longwall system's devices was developed using IFIX visualization software. In addition, two independent monitoring-and-diagnostics tools, NEMAEQ SDA and ITGKomMoxaMenager, were developed.

The following synoptic screens and their areas responsible for visualization of each machine of the longwall system are included in the main visualization:

- Synoptic screen of operator's station, which is the main form of process state visualization
- Shearer's screen
- Conveyor's screen
- Trend screens
- List of alarm states

The role of these synoptic screens and the areas of visualization for each element on the longwall system are outlined below.

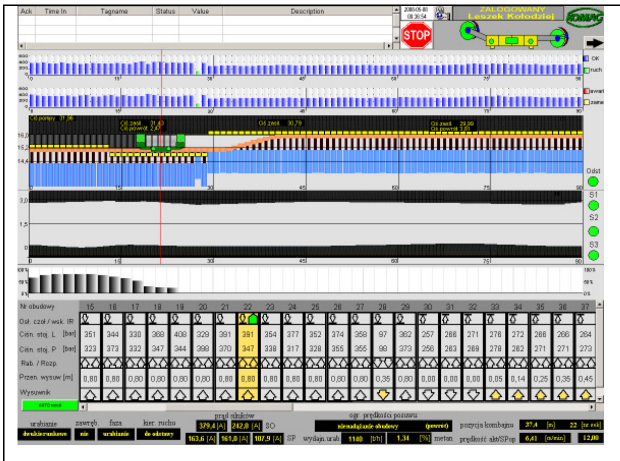


*Figure 3.3.3-1: Main operator's display*

*Figure 3.3.3-2: Shearer display screen*

The synoptic screens and databases of the visualization system are configured in a semi-automatic way using scripts that define the number of roof supports, dimensions of supports and the shearer as well as the screen resolution. The scale of presentation of the roadway is differentiated depending on the length and transverse dimensions of the longwall, in order to show more clearly the position of the support and AFC at small web depth in relation to the longwall length.

The main operator's display ***(figure 3.3.3-1)*** includes a list of the latest high priority alarms. The main objects show conditions of operation, stoppage or failure, as well as the main parameters of the machine, position of the shearer, supports, AFC and front shields and the roadway profile. They include screen parts showing pressure in props, longwall view from the top, mined roadway profile, degree of AFC load, support's parameters, main parameters of the cutting process and pressure distribution in the main pipelines of the support hydraulic system, as well as a side view of the shearer.

The shearer display screen ***(figure 3.3.3-2)*** contains a shearer schematic diagram and a list of the main parameters, keys used for modification of displayed trends and to open the windows of complementary parameters. The shearer view enables control of the arms and loader's position and also control of the drive condition. Colour indicators of advance drive's state and collective indicator of correctness of other systems are included on the shearer display. The shearer schematic indicates the state of the cutting drum by changing color. Indicators of the motor status are, for normal motor operation, grey to show intended switch off, or red in the case of failure. Indicators of the status of other devices are a green colour for the case of correct operation, or red in the case of a failure that stops the machine. The key shearer parameters displayed include:

- Current intensity in the cutting drum motors and advancing system motors (averaged for 3 s.).
- Position indicator of the cutting drum and loader that includes the inclination angle of the shearer arm, turning angle of the loader arm and height of the cutting drum axis over a conventional longwall face edge on the outbye side.
- Estimated cutting drum efficiency.
- Pressure of the cooling and spraying water (placed respectively on the left and right side of the shearer).

The lower part of the shearer display presents real-time graphs of motor current and advance speeds.

The conveyor display screen provides more detailed parameters connected with operation of the conveyor drives such as:

- control lights of the conveyor motor (maximally 4), identical to that on the shearer's screen, presenting a total time of operation since the beginning of longwall mining, and indicators of the motor state, current intensities, momentary and averaged (for the assumed period of time)
- estimated mining output and weight of transported material on the conveyor
- graphs of momentary and averaged current in the motors, together with a legend of colours of each line and keys that enable the operator to turn on, or off, the generation of graphs.

Trend screens are provided to display changes in the parameters of the longwall system's machines over time. Both real time trends and historical graphs, which use the parameters collected in databases can be displayed.

List of alarm states – alarms are divided into groups connected with the main subassemblies of the longwall system – the shearer, powered roof support and AFC. A specific priority (0 - 2) is allocated to each alarm and warning state. The latest 3 high priority alarms are presented on the main operator's display, whereas the alarm display screen can be used to examine all current and historical alarm and warning conditions.

***NEMAEQ SDA***

NEMAEQ SDA is an expert system that has been developed as a diagnostics tool for the visualization system. This system allows online communication with the machines of the longwall system via existing communication systems, or it can use data that has been collected via equipment memory cards to populate the server's relative databases.

Two example diagnostics screens are shown in ***figures 3.3.3-3*** and ***3.3.3-4.*** The first screen enables examination of the collected data using charts of selected variables. Analysis is carried out for one hour intervals. Free scaling and zooming of the generated diagram is possible. Information from the charts window is used to assess the correctness of the diagnostics system. It is correlated with the information displayed on the second diagnostics screen i.e. on the machine's visualization screen.

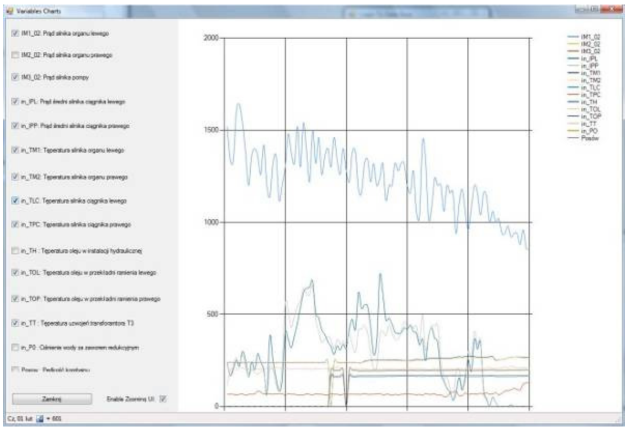


***Figure 3.3.3.-3: Charts Screen***

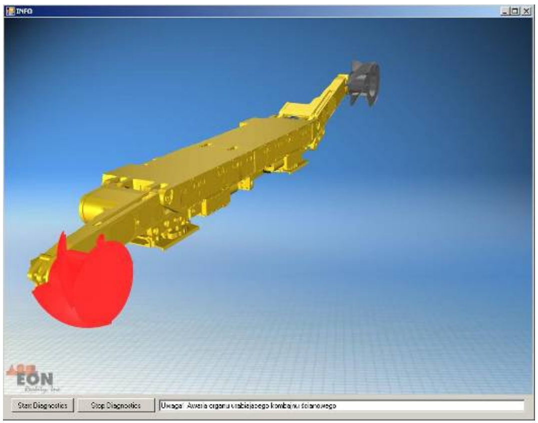


***Figure 3.3.3-4: Diagnostic Screen***

The software analyzes the technical condition of the machine and, in the case of alerts or failures, it generates reports and presents the machine in a 3D view highlighting the reported anomaly. The software can also communicate with electronic operational documents that were developed by KOMAG.

Modification and correction of the system's knowledge base is indispensable to ensure that the expert system is running properly. For browsing and editing the knowledge base, the software is equipped with a window that can realize these operations. The method of recording knowledge base and machine failure will be presented in an enclosure to the report using an example from the longwall shearer.

A more detailed description of the visualization system is presented under ***6.1.3, page 124.***

***Application considerations for an oil contaminant monitor***

The work carried out was reported in detail in an internal technical report, D3.2 *Investigation / Recommendations on Candidate Methods of Oil Contamination Monitoring*, and is summarised below.
An analysis of oil contamination classes and causes was undertaken. Consideration was given to contaminants originating in the water cooling system, from machinery wear, in internal combustion engines, from chemical breakdown of the oil, and from the environment. The conclusion drawn was that particular attention should be given to monitoring aqueous contamination. Nevertheless, the prevalence of coal dust contamination and metallic wear particles (which might have a masking effect on the detection of water) was noted.

A review was undertaken of methods for measuring the concentration of water in oil. In order not to be unduly influenced by common practice, the review was wide-ranging, including methods that are normally considered applicable only for off-line testing, and on-line methods that are normally used in the oil supply industry, as opposed to monitoring hydraulic and lubricating oils. The following methods were considered:

- Visual crackle test
- Calcium hydride test
- Water by distillation
- Karl Fischer method
- Two-plate capacitance
- Thin-film dielectric capacitance
- RF resonance measurement
- Infrared absorption
- Photoacoustic spectroscopy
- Microwave Absorption
- Density-based method (Coriolis)
- Heat transfer
- Ultrasonics

For each of the above methods, consideration was given to the principles of operation, and typical applications, with reference to the pros and cons for on-line monitoring of hydraulic and lubricating oils in the mining industry. Also, commercial product offerings were appraised.

It was concluded that capacitive methods offer the best compromise solution, taking into account factors such as sensitivity, accuracy, low-complexity, durability, and low maintenance overhead. Both twin-plate and thin-film dielectric capacitive methods are worthy of consideration, although it must be recognised that the two techniques provide different metrics. Twin-plate capacitive sensors measure the absolute water concentration with no upper measurement limit. Thin-film dielectric capacitive sensors measure the degree to which the oil is saturated with water. Tribologists consider this to be a more useful measure of impending damage, but it is insensitive to increases above the saturation level. Infrared absorption was also considered to be a potentially useful technique (especially as sensors can also be designed to detect other contaminants), although the extra complexity and cost, compared to capacitive methods, was of concern.

### 3.3.3.2 Development of monitoring hardware (thermal imaging camera, wireless sensors, water in oil transducer

***Thermal Imaging Camera***

The need for the development of the thermal imaging camera origins in the limited approval of the existing CdF camera which is certified to ATEX M2 only; this restricts its use for applications requiring anM1 cerification. The CdF camera was manufactured in a small batch only and subjected to unit verification certification by INERIS, the Notified Body. This approach is very expensive and only suited for the limited numbers of units required by CdF for their shaft inspection work. The wider applications under consideration within NEMAEQ dictate a requirement for a low cost, volume product.

The thermal imaging camera was developed in multiple steps. At the first stage, analysis of the requirements was performed ***(figure 3.3.3-5).*** It was backed up by measurements taken in the underground workings of Chwalowice mine (during task 3.1, chapter 3.3.3.1), using high end thermal imaging equipment.

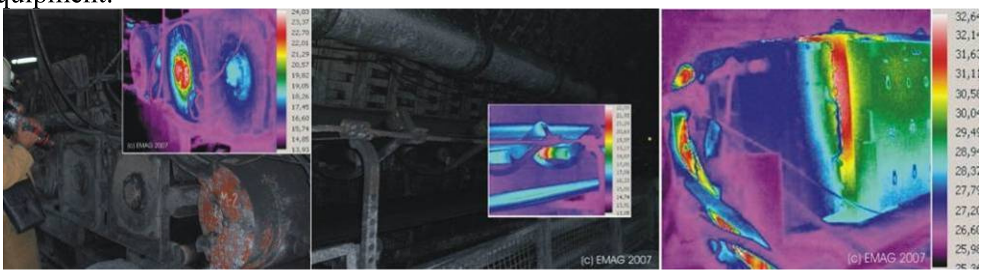



***Figure 3.3.3-5: Requirements analysis stage – data from Chwalowice-Rybnik coal mine***

As a result, a specification for the optical and electronic components of the camera was developed. In a second step, a development platform for the camera was designed and fabricated. It consists of an ultra low power programmable logic board and two custom boards for digital signal processing and analogue interfaces (***figure 3.3.3-6a***). Once the key optical components were obtained, the platform was integrated and used for the development of the camera software (i.e. image correction algorithms, device drivers).

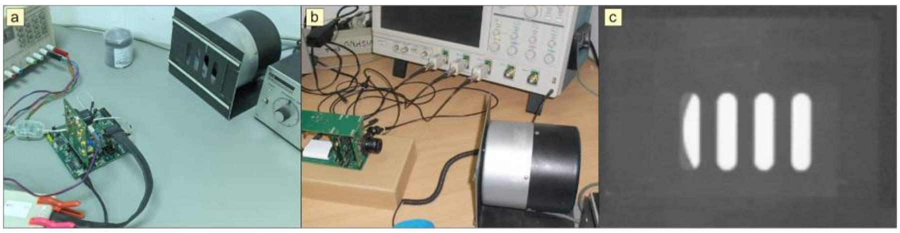



***Figure 3.3.3-6: (a) Development platform, (b) prototype electronics, (c) sample thermogram***

Special attention was paid to image enhancement algorithms, to achieve a high quality of the thermal images (even for low thermal scene dynamics) and operation without the use of a thermoelectric stabiliser. This was possible through implementation of non-uniformity correction and dynamic scene adaptation algorithms.

The development platform was also extensively used for an optimisation of the electronic modules, especially low noise biasing circuits which in a final revision were adapted to handle the higher current demands of a 320x240 resolution sensor. As soon as the major functionality was achieved, the printed circuit boards for the prototype were designed and then fabricated using multi-layer technology, improving EMI and noise performance. The prototype (***figure 3.3.3-6b***) was then further optimised in terms of software development and enhancements made to the electronic modules. Once the sufficient performance was achieved, the electronic modules were mechanically integrated with the CAD designed enclosure of the prototype unit (***figure 3.3.3-7***).

Thanks to the high degree of flexibility, which was achieved by employing low power programmable logic, it was possible to interface to new 'future proof' type of 320x240 pixels IR sensor as well as to adapt to a new type of micro display (because the former revision became obsolete). The developed device, in an innovative way, combines the advantages of low power electronics design with the employment of advanced data processing, enabling operation without a power consuming thermal stabiliser. This ensures operation at very low power levels (< 2W), which was essential in achieving an ATEX eligible design.

***Figure 3.3.3-7: Prototype thermal imaging camera***

To accomplish the requirements within the project, the camera provides significant enhancements, e.g. automated measurement capability and state-of-the-art imaging performance. In terms of thermographic performance the camera is based on low power 160x120 microbolometer sensor. The sensor can be replaced seamlessly by a 320x240 compatible sensor giving outstanding thermal picture quality for more demanding applications.

***Wireless diagnostic sensor network***

Part of the activities was dedicated to the introduction of necessary modifications to the wireless gateway and router nodes (derived from developments of the RAINOW project), in order to make possible their operation in the longwall area. These modifications included introduction of an RF power amplifier stage, to ensure sufficient radio coverage, and development of a mechanically robust antenna (see ***figure 3.3.3-8 a, b***) to replace the former fragile dipole version. The modular design (base board + RF module) was improved (a few interface signals were added and connector footprints were updated) in order to enable integration with different RF modules for future proof applications. Finally the old type of connectors were replaced by stainless steel IP68 fast connectors compatible with the interfaces of FO transmission devices developed in WP4. The final design is depicted in ***figure 3.3.3-8c***.

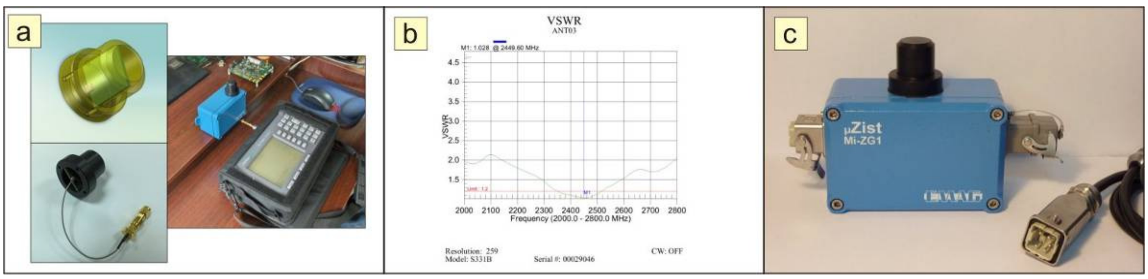


***Figure 3.3.3-8: Prototype wireless gateway/router node***

The wireless diagnostic sensors were developed to meet the specific demands of machine monitoring applications. The developed devices are based on a high performance low power microcontroller of the MSP430 family and employ low power wireless technology to ensure long battery operation. The sensors are based on a unified hardware platform (see ***figure 3.3.3.8a***) consisting of the baseboard with the MCU and the wireless module with an integrated high performance ceramic antenna. The final revision of the enclosure for the sensors (measuring 80x70x35mm) was designed to have a high environmental protection rating (IP68). The developed types of diagnostic devices include: vibration, temperature, liquid presence and water-in-oil sensors.

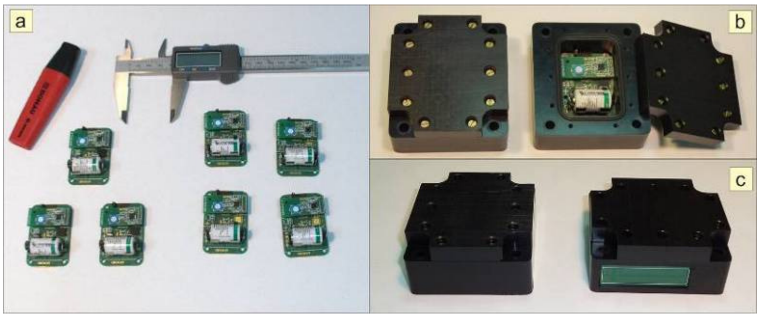



***Figure 3.3.3-9: Prototype wireless diagnostic sensors***

*Vibration sensor* ***(figure 3.3.3-9a)*** is based on a 3-axial micro-machined (MEMS) acceleration sensor (measurement range +/-6g) characterised by high temperature operation and high shock resistance. The vibration measurement bandwidth is 600Hz, sample resolution 12-bits. The final software revision for the vibration sensor allows a data acquisition scheme to be operated, which is adequate for carrying out FFT based spectral analysis (buffering allows 512 FFT points for each axis).

*Temperature sensor* ***(figure 3.3.3-9b)*** is based on a digital high resolution temperature sensing element, enabling an accuracy of 0.5°C and 13-bit resolution within a -55°C÷125°C range to be achieved. The hardware is designed to enable the integration of a temperature and a vibration sensor in a single enclosure.

*Water presence/level* ***(figure 3.3.3-9c)*** contains additionally a separate printed circuit board with a capacitance converter and two sets of sensing electrodes. It measures capacitance change caused by the change of environment permittivity. It was also used during the development of the water-in-oil sensor described below.

***Water in oil transducer***

The review of methods for monitoring water in oil, carried out under Task 3.1 (chapter 3.3.3.1), recommended a comparative evaluation of commercial sensors, based on both twin-plate capacitance and thin-film dielectric capacitance principles. The former responds to changes in bulk permittivity arising from significant oil contamination, whilst the film type sensors respond essentially to the dissolved water content of the monitored oil, and are hence significantly more sensitive.

A survey was also conducted with all partners to establish which gearbox and hydraulic oil types are in common use, and which representative types should be selected for testing purposes in a test rig. The survey confirmed that several commercial oil types are in use throughout the mining and mineral extraction industries of the European Union. Typical gearbox oil is ISO VG 320 grade mineral based oil. However, there is also an emerging trend of considering the use of synthetic oils, where mean gearbox power levels are very high and maximum operating life is critical. Based on this survey, discussions with UK Coal Mining Limited and UK specialist oil suppliers, Fuchs *PowerGear* and *PowerDraulic* oil types were selected for testing purposes. These oils are in general use in the UK, are readily available, and are supported by a significant body of off-line analysis data.

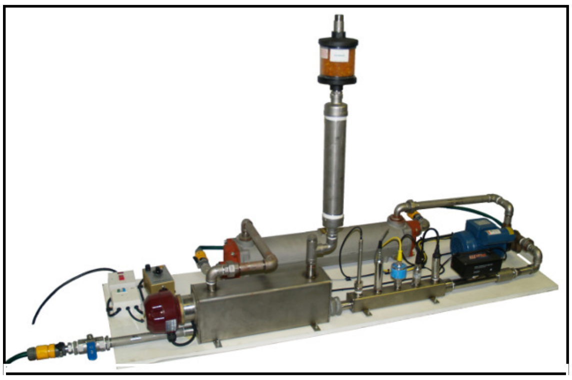


***Figure 3.3.3 – 10 Oil in water transducer test rig***

The test rig shown in ***figure 3.3.3-10*** was designed, built and commissioned and a programme of experimental work undertaken to evaluate the comparative performance of six commercially available sensors that were obtained for testing and evaluation purposes. The tests involved the following procedures, in each case logging the results of each of the sensors simultaneously for subsequent comparison, together with a temperature reading:

- Monitoring the output of the sensors, while heating the oil from 25°C to 70°C and then cooling it again to 25°C, with no added water and with five measured amounts of water in the oil, calculated to give a water-in-oil concentration ranging from 200ppm (which is typical for new oil) to a point beyond saturation.

- Monitoring the output of the sensors, while heating the oil from 25°C to 70°C and then cooling it again to 25°C, with a single measured amount of water, in the presence of a worst-case concentration of finely-divided coal dust, a likely contaminant in mining machinery, which is a potential masking agent in the detection of aqueous contamination.
- Monitoring the output of the sensors, while heating the oil from 25°C to 70°C and then cooling it again to 25°C, with a single measured amount of water, in the presence of a worst-case concentration of finely-divided iron powder (to emulate metallic wear particles), a likely contaminant in mining machinery, that is a potential masking agent in the detection of aqueous contamination.

The contaminants use in the test rig were selected and measured to be representative of contamination found locally and in machine sections. A sequence of tests was undertaken where the level of contamination was progressively increased by the addition of precise amounts of contaminant. Off-line confirmatory analyses using Karl Fischer titration and particle measurement-particle chemistry determination were conducted by a NAMAS accredited test house.

A summary of the performance of each of the sensors is given in ***Table 3.3.3-1.*** Colour coding has been used to give a broad indication of a comment that is favourable (green), intermediate (yellow or orange of which yellow is the better), or unfavourable (red).

| Manufacturer | Model | Measures | Primary Tests | | Solid Contaminant Tests | |
|---|---|---|---|---|---|---|
| | | | POWERGEAR with water only (5 tests) | POWERDRAULIC with water only (5 tests) | POWERGEAR with water and coal dust (2 tests) | POWERGEAR with water and iron powder (2 tests) |
| EESIFLO | EASZ-1 | Absolute concentration (i.e. twin-plate sensor) | Highly insensitive. Produced output indicating an absolute concentration of no more than 100ppm during gradual heating at all concentrations up to 1,200ppm. During rapid cooling gave readings of up to 1,500ppm but only intermittently. | Only test at 200ppm conducted. Output (which should be independent of temperature) varied considerably during heating and cooling periods. Output over most of the temperature range was higher than the actual value by a factor of ten. | Presence of coal dust gave readings that differed by ~10% up to 35° but which were little different at higher temperatures. | Presence of coal dust gave readings that differed by ~10% up to 35° but which were little different at higher temperatures. |
| Industrial Monitoring Systems | Moist Alert | Saturation level (i.e. thin-film sensor) | Gave qualitatively expected readings only at 200ppm, 400ppm and 600ppm although glitches were present at this latter concentration. Highly erratic behaviour at higher concentrations. | Gave qualitatively expected readings only at 200ppm, 400ppm and 600ppm although many glitches were present at the latter two concentrations. Highly erratic behaviour at higher concentrations. | Presence of coal dust produced little difference to the output. | Presence of iron powder gave readings that differed by ~19% at 25° and ~6% at 70°C from the results with water only. |
| Kittiwake | ANALEXrs Moisture Sensor | Saturation level (i.e. thin-film sensor) | Gave qualitatively expected readings only at 200ppm and 400ppm. Periods of reverse trends (i.e. rising saturation level with rising temperature) and erratic behaviour occurred at higher concentrations. | Gave qualitatively expected readings at all concentrations with the exception of a slight reverse trend (i.e. rising saturation level with rising temperature) occurred at 400ppm. | Presence of coal dust produced little difference to the output. | Presence of iron powder gave readings that differed by ~20% at 25° and ~8% at 70°C from the results with water only. |
| Parker Hannifin | MS100 | Saturation level (i.e. thin-film sensor) | Gave qualitatively expected readings only at 200ppm. Periods of reverse trends (i.e. rising saturation level with rising temperature) occurred at 400ppm, 600ppm and 800ppm and erratic behaviour occurred at 12,200ppm. | Gave qualitatively expected readings only at 200ppm. Periods of reverse trends (i.e. rising saturation level with rising temperature) occurred at 400ppm and erratic behaviour occurred at higher concentrations. | Presence of coal dust gave readings that differed by 15%-20% from the results with water only. However, since the difference for 65mg coal was greater than that for 250mg coal, there is the possibility that this observation is purely a function of non-consistency in readings. | Presence of iron powder gave readings that differed by ~10% at 25° and ~5% at 70°C from the results with water only. However, since the difference for 675mg iron was greater than that for 2.5g iron, there is the possibility that this observation is purely a function of non-consistency in readings. |
| Schroeder | TWS-C | Saturation level (i.e. thin-film | Gave qualitatively expected readings at all concentrations except for | Gave qualitatively expected readings at all concentrations although | Presence of coal dust gave readings that differed by up to 15% at | Presence of iron powder gave readings that differed by ~10% at 25° |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | sensor) | a tendency toward reverse trends (i.e. rising saturation level with rising temperature) at lower temperatures. | the output for 1,200ppm was much the same as for 800ppm suggesting less sensitivity than the Vaisala MMT318. | low temperatures but much less at higher temperatures. | and ~4% at 70°C from the results with water only. |
| Vaisala | MMT318 | Saturation level (i.e. thin-film sensor) | Gave qualitatively expected readings at all concentrations. | Gave qualitatively expected readings at all concentrations. | Presence of coal dust produced little difference to the output. | Presence of iron powder gave readings that differed by ~14% at 25° and ~7% at 70°C from the results with water only. |

***Table 3.3.3-1 – Summary of Performance of Each of the Sensors Evaluated***

It was concluded that the Vaisala MMT318 outperformed all the other sensors in the primary tests and left only a slight cause for concern in respect of its performance in the presence of a high concentration of iron powder (i.e. metallic wear particles). This was considered only a minor issue in that metallic wear particles are thought to be mainly a secondary contaminant, the concentration of which will be minimised by effective monitoring of aqueous contamination. An internal report, *Technical Report: Evaluating Commercial Water-in-Oil Sensors*, which details this work was prepared and distributed to project partners.

As a result of the conclusion that the commercially available Vaisala MMT318 water-in-oil sensor outperformed all the other sensors, and provided expected results under virtually all test conditions, work was undertaken to examine its potential for use in practical mining applications. This work examined the feasibility of implementing an ATEX M1-M2 version of the water-in-oil transducer to enable field trials to be undertaken and is reported under chapter 3.3.5.2.

Whilst it was found to be technically feasible to adapt existing products to produce an ATEX M1 or M2 certificated water-in-oil transducer, physical constraints and commercial considerations indicated that the realisation of a device for use in practical mining applications was uncertain and, at best, likely to result in long lead times before practical industry benefits are realised. Consequently, an alternative solution that would facilitate a more immediate practical implementation strategy was investigated.

Building on the insights into the most appropriate principles for sensing water in oil for mining applications gained from this research, and the "water presence/level" sensor being developed as part of the wireless machine monitoring sensor network, additional collaboration between partners led to the development of a proof-of-concept prototype of a water in oil (water activity monitoring) sensor.

The developed sensor ***(figure 3.3.3-11)*** uses a thin film capacitive sensing element (***figure 3.3.3-11a)***. This device employs a specially modified capacitance sensing circuit derived from the sensor design originally used in the water presence detection /water level sensor. The additional enhancements introduced allowed interfacing to the sensing element of ten times higher bulk capacitance whilst maintaining the converter readout linearity.

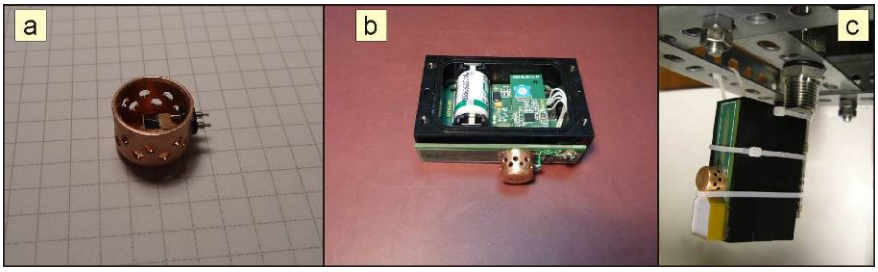



***Figure 3.3.3-11: Prototype wireless water in oil sensor***

Tests were carried out to evaluate the performance of the prototype using the Vaisala MMT-318 as a reference source (see chapter 3.3.5.2). The results obtained showed that the performance of the prototype was comparable with the best of the currently available commercial sensors and also suggested that calibration against particular oil types may not be necessary. As a future enhancement, thermal compensation could be introduced; this should not be difficult, as the converter has an integrated temperature sensor of sufficient accuracy.

All the wireless sensors developed by the project are designed to operate at minimum power supply levels. This was achieved by employing ultra low power components, careful design of the electronic modules and advanced power management strategies implemented in the embedded software.

An examination of mechanical life, as a function of water in oil concentration, confirmed that component life is critically affected by the water in oil content, and that ideally water in oil content needs to be maintained below 50ppm – 100ppm. For this reason, the programme was extended slightly to examine the options available for actively scavenging and sequestering oil from machine sections. It is projected that an effective oil contamination control strategy, achieved through on-line monitoring and active water removal, has the potential to reduce a number of machine early life failures. The findings of this additional research were documented in a Technical Report: "Evaluating Desiccants for Removing Water from Oil" and circulated to project partners.

#### 3.3.3.3 Identification and delineation of existing maintainability issues and limitations

Maintenance operations on coal face equipment were studied, both in Poland and the UK, to identify the operational task requirements and maintenance limitations most likely to arise as a result of the equipment design or the working environment in which the maintenance is undertaken. The central objective of these studies was to obtain the fundamental data and information required to produce the software tools being developed under Task 3.4 (chapter 3.3.3.4) *"Development of Maintainability and Human Reliability assessment tools"*.

It was concluded that to enable an overall assessment of maintainability for a given machine it is necessary to consider the interactions between the range of maintenance tasks typically required to install and maintain machines at their optimum operational efficiency and the factors that influence the performance of the artisans conducting these tasks. To provide a representative sample of maintenance tasks, a range of typical operational activities were examined.

These include:

- Initial assembly and installation of longwall equipment
- Routine servicing tasks
- Breakdown and / or repair activities
- Relocation of the machine – disassembly, transportation and reassembly

The activities required of maintenance workers to undertake these tasks were evaluated in the light of the equipment's design and any health, safety or ergonomic constraints that the design of the equipment, or the working environment, may impose. These constraints serve to increase the physical difficulties encountered whilst performing maintenance work and hence are referred to as "maintainability limitations".

A wide range of maintainability limitations, imposed both by the working environment and equipment design, were identified. The maintainability limitations identified, and the factors that contribute to the severity of these limitations, were divided into two main groups:

1. **Environmental factors -** the limitations that arise primarily as a result of the underground environment in which the maintenance operations are conducted. The main environment factors identified include:
   - **Workspace restrictions** – these frequently lead to manual work having to be performed whilst adopting awkward postures. Additionally, some maintenance operations require the construction of additional safe working spaces before they can be undertaken.
   - **Illumination** – maintenance tasks frequently require higher levels of illumination for them to be conducted correctly, compared to those required for routine production tasks. Consequently, temporary supplementary illumination may be required.
   - **Climatic conditions** – adverse climatic conditions such as high temperature and humidity serve to exacerbate the physical effort required and to increase the likelihood of human errors and procedural violations occurring.

2. **Equipment factors -** the limitations that can be attributed primarily to the design and nature of the machines and equipment being maintained. The main equipment factors identified include:

- **Access restrictions - lack of access is generally the greatest single cause of poor maintainability. Of the different forms of access problem identified, the most common and influential, in terms of maintainability, are**:
  - Restrictions and obstructions which limit the ability of workmen to see, reach, grasp and manipulate components.
  - Limitations in aperture sizes which inhibit the ability of workmen to carry out the required tasks within these apertures.
  - Limitations in the clearances available around fasteners which prevent the straightforward application and use of tools.
- **Lifting and handling -** To enable them to withstand the rigours imposed by the harsh environment, almost all mining machinery and their component parts are heavy. Consequently, maintenance operations almost invariably involve the removal and replacement of heavy parts, sub-assemblies, cover plates, etc. The primary factors identified as adversely influencing maintainability include:
  - Limited provision of lifting points on component parts
  - A need to construct and employ special/temporary lifting arrangements
  - The shape and instability of components and sub-assemblies

To further facilitate the development of maintainability assessment tools, data derived from the examination of maintenance tasks was also used to identify and define the key characteristics of a generic set of maintenance task elements. These task elements included:

- Removal and replacement of hatches and covers
- Working in/through apertures
- Changes of location (Moving around the equipment)
- Access restrictions for tools
- Number and type of fasteners to be remove/replaced
- Machine component removal and replacement
- Preparation of work area etc…
- Fluid Checks – oil/water levels
- Component Checks – wear, belt tension, etc.
- Lubrication/greasing
- Draining and filling oils etc…
- Cleaning & contamination potential
- Adjustments

The results and conclusions derived from this task were reported in detail within project deliverable report D3.4 - "Limitations in the Maintainability of Mining Machines". This report provided the baseline data required by T3.4 to enable the development of the maintainability assessment tools.

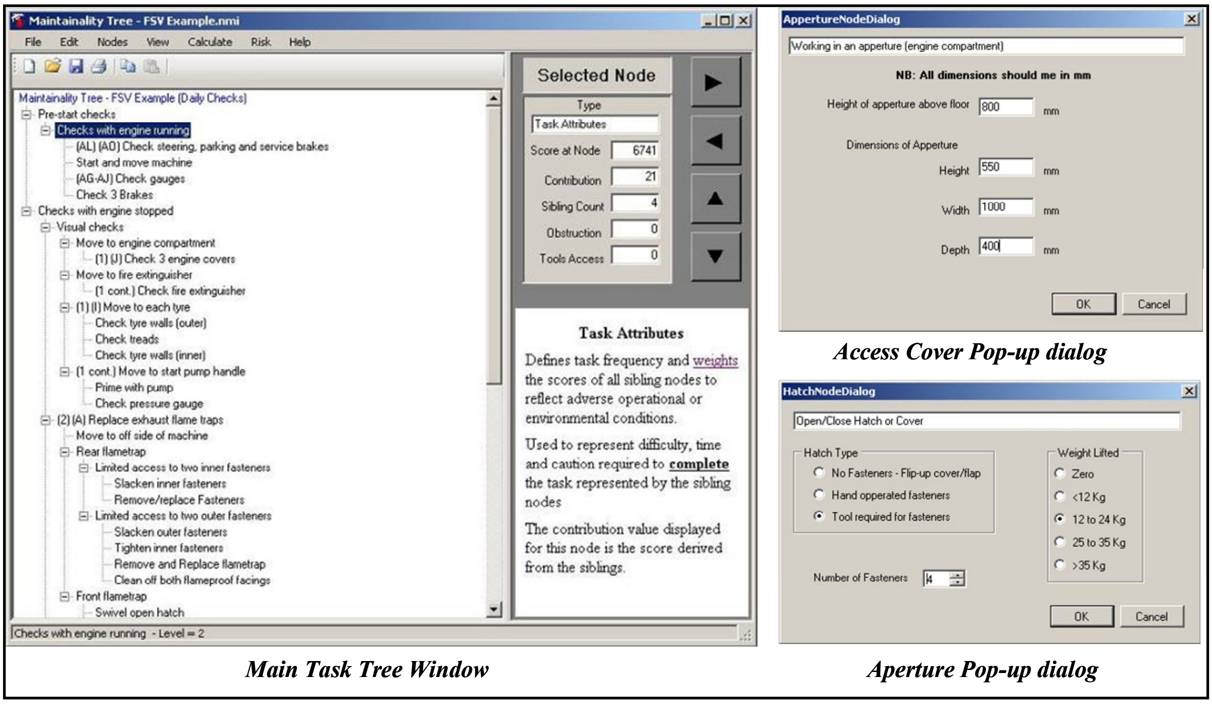
#### 3.3.3.4 Development of Maintainability and Human Reliability assessment tools

A range of Maintainability and Human Reliability assessment techniques were investigated to identify those with the potential to be developed, refined and integrated into a software toolkit that would:

- Provide indicative measures of operational down time, and hence cost
- Highlight critical task elements - those where improvements or change would have most impact on cost and human reliability
- Identify the potential for health and safety risks and critical human errors to arise.

The central component of this toolkit, the maintainability assessment tool, was designed to enable end-users to examine the time and effort required to correctly conduct maintenance tasks and to identify equipment design limitations that have a significant impact on the time taken and/or reduce the probability of the tasks being correctly completed. The maintainability assessment tool allows the user to model virtually any mining maintenance task for the specific items of equipment being examined. This is achieved by developing hierarchical task descriptions from a selection of software objects that model each of the generic maintenance task elements identified under Task 3.3 (chapter 3.3.3.3).

The software design philosophy adopted throughout the project was to keep the user interface simple and as close as possible to other windows based software applications to minimising learning time for the end users whilst maximising usability. Hierarchical task analysis data is entered, presented, and edited using a hierarchical tree view that is similar to those encountered in many MS Windows based programmes. ***Figure 3.3.3-12*** shows an example of maintainability assessment dialog windows with part of a hierarchical task description displayed in the main tree view window.




***Access Cover Pop-up dialog***

***Main Task Tree Window*** ***Aperture Pop-up dialog***

***Figure 3.3.3-12: Example Maintainability Assessment Dialog Windows***

The hierarchical task description developed in the main tree view windows is built up from a series of software objects that model the generic task elements identified by the project. One group of software objects, like the Hatch/Cover object shown above, produce a metric that directly reflects the time and effort typically required to conduct the task element they represent. Pop-up dialogs are used to define the variables required to model the task elements. In the case of the Hatch/Cover object, the time and effort required to remove and replace a hatch or cover is derived from the style of cover, the type and number of fasteners involved and the forces required to lift and/or remove it.

A second group of objects, like the aperture object shown above, is used to weight the scores generated by all the subservient objects. Hence, in the case of an aperture object, weightings are applied to reflect the additional time and effort likely to be incurred as a result of the access restrictions it imposes on all of the subservient objects/tasks elements (i.e. the task conducted within the restricted aperture).

Development, testing and refinement of the task objects and the user interface were an integral part of the development process throughout the duration of the project. This was achieved by making comparisons with the results from past hierarchical studies of mining machine maintenance tasks and the practical trials conducted under Task 5.3 (chapter 3.3.5.3).

The user interface enhancements and analysis software improvements identified by this process included re-structured task element/node selection windows and a context sensitive help system.

To provide additional tools that would assist the industry to identify sources of potential human error and hence improve human reliability during maintenance operations, research into a range of assessment techniques was undertaken, to identify approaches that could be employed to highlight critical task elements where improvements or change would have most impact on cost and human reliability. This research led to the identification and further development of a human error classification framework to address maintenance related issues and the selection of two human error 'diagnostics' that would be suitable for use with the maintainability assessment tool. These 'diagnostics' are a risk perception and hazard awareness measurement technique and a violation potential assessment questionnaire.

***Risk perception and hazard awareness***
Traditionally, this technique involved conducting structured interviews with members of the work force during which they would be asked to estimate the riskiness of particular actions. By obtaining an estimate of the level of risk that is perceived by workers to be involved in a particular action, one can obtain an indication of the likelihood of that action being taken by the individual concerned. Consequently, work was undertaken to develop an improved risk perception measurement approach that could be integrated with the maintainability assessment software. This provides a mechanism that can be used to identify those task elements with an elevated risk of violating behaviours that lead to tasks being performed incorrectly or even missed out completely.

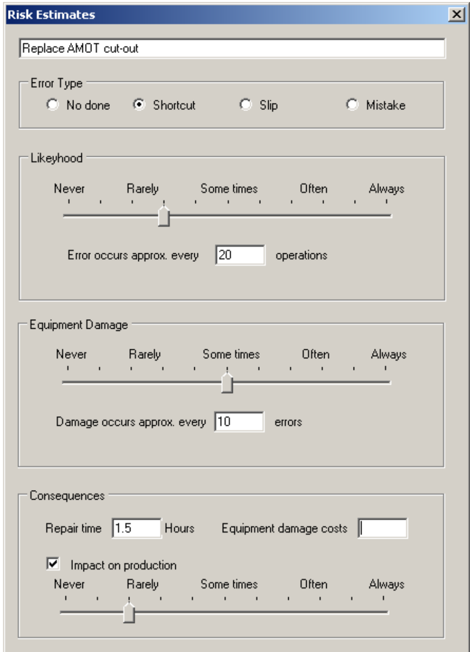


***Figure 3.3.3-13: Risk estimation dialog box***

Additional software modules, to allow user estimates of risks to be included directly into the maintainability assessment tree structure, were designed and produced. User feedback from T5.3 was used to identify the preferred interface design elements from a range of possible dialog window designs that were initially prototyped. The user preferred options were employed in the production of the risk estimation dialog shown in ***Figure 3.3.3-13.***

***Violation potential assessment***
A questionnaire based approach designed to assess violation potential was investigated. It is important to note that the objective of this questionnaire is to assist management to identify actions that they can take to reduce the risk of violations occurring. It is not designed as, or appropriate for use as, a means to identify individuals that may potentially be more likely to violate rules.

The underlying measurement technique being employed relies on the attitudinal questionnaire being completed by a sample of the workforce. This measurement approach can only produce meaningfully results if the questionnaires are used to assess a specific task that would normally be undertaken by the selected survey participants.

Initially analysis of the responses to the questionnaires and discussions with the participants indicated that their responses tended to be unduly influenced by the generic problems they encounter in their day-to-day work, rather than focusing strictly on problems that were directly relevant to the task being examined.  It was postulated that this problem arose mainly as a result of having to include “generalised” descriptions in the question set to allow a standard “paper based” questionnaire to be produced. To combat this problem, an “electronic” version of the questionnaire that allows descriptors like “the job” to be quickly and easily replaced by more specific and meaning full descriptors was produced.

It would be impractical to attempt to asses all of the maintenance tasks conducted on a mine at this level of detail. Hence, an initial screening process was required that could quickly and efficiently focus management's attention on those jobs which show, at least superficially, the greatest potential sources for violation problems. To this end, a simple checklist approach was examined to determine if it could be successfully used to help focus management on the job categories where, on balance, the probability of rule violations is highest. Results from user trials indicated that this simple screening approach helped to identify those maintenance tasks that would benefit most from the more rigorous examination of violation potential provided by the violation potential questionnaire.

Consequently, this checklist has also been integrated into the maintainability software. However, it is also noted that, in many cases, experienced maintenance managers and supervisory staff were able to readily identify many of the key tasks where violations were most likely to lead to significant problems.

## 3.3.4 Data transmission by FO based Fieldbus-Systems (WP4)

### 3.3.4.1 Basic Research and Technology Selection

It is well-known that Fiber Optic (FO) based data transmission systems have significant potential advantages over copper systems. However, the design of a FO cabling system could take long time and the final cost could be high. For this reason, a system requirements analysis and the selection of appropriate elements is an important task to do at the beginning of any development.

In order to fulfil the requirements of the major number of applications as possible as well as getting an open system according to the industry standards, the next features were defined as the most appropriates to be provided to the communication system developed under the current project:

1. **Architecture:** FO based Fieldbus, with intrinsically safety power on the same cable.
2. **Data Tx performance:**
   a. At least 10Base-F (10 Mbit / s @ 1000 m) in non-repeater long runs
   b. Desirable 100Base-Fx (100 Mbit/s) in shorter runs, around 183 m. Please note that this length, although sufficient for practical purposes, is below 100Base-Fx Spec (412 m for a single, non repeater segment).
3. **Interfaces:**
   a. Fiber optic access point
   b. Media converter to TTY (PLC and other legacy equipment).
   c. Media converter to RS485 (PLC and other legacy equipment).
   d. Media converter to 10/100Base-Tx.
   e. Or direct connection to FO aware equipment.
4. **Physical / environmental:**
   a. Cabling system adequate for mine use: Water, oil and hydraulic fluids resistant, bend and crushing resistant.
   b. Using connectors for fast deploy – rearrangement.
   c. The naked FO core of the unconnected parts must be protected for decreasing the influence of dust in connectors.

This new Tactical System is aimed to be installed only in areas where its benefits and special properties are required, maintaining the current FO communication structures based on trunk backbones to cover long distance links. Consequently both systems would be capable of being easily integrated.

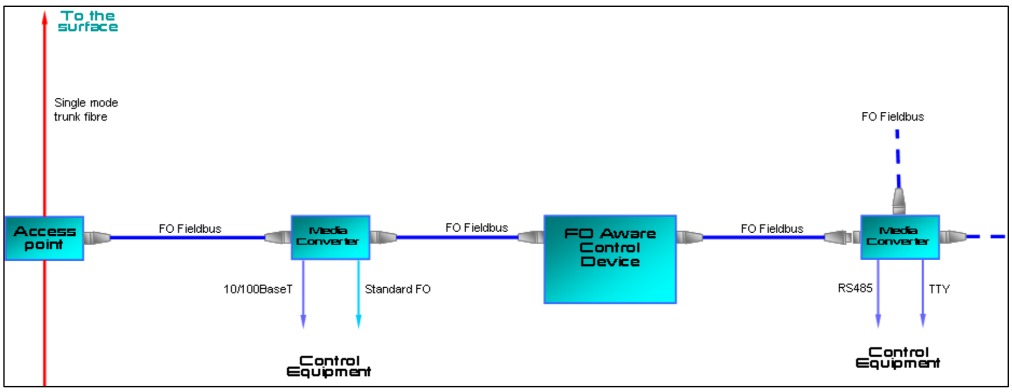



*Figure 3.3.4-1: FO Fieldbus concept diagram*

***Basic Concepts about Fiber Optic***

In order to understand some issues both in the selection of the kind of fiber optic and the optic contact development, some basic concepts must be explained.

In simple words, a FO is a highly transparent conduit of plastic or glass which can guide the light across it. An FO does not allow light escaping by other point than its end, acting like a sort of pipe for light. The physical principle that allows the operation of a FO is a side-effect of the Snell law called "total reflection": A beam of light that propagates across a material of refractive index n1 (core) will be reflected totally when it meets another material with a refractive index n2 (cladding), if n1>n2, and the angle between the beam and the normal to the contact surfaces of both materials is higher than a "critical angle" determined by the relation of the reflective indexes.

For the same physical reason, it exists a limit angle for light able to go into and propagate along the FO. This angle $\theta_a$, referenced to the axis of the fiber, determines a characteristic parameter of every type of fiber, called Numerical Aperture ($NA = sin(\theta_a)$), which defines the so called acceptance cone. Light entering the fiber within the acceptance cone will propagate along the fiber, while light out of it will exit the fiber by the interface with the cladding and will not propagate.

This parameter is critical for the determination of the physical properties of the system, imposing constraints and requirements to the precision (tolerances) in the dimensions of mechanical elements like connectors or transceivers. The ***figure 3.3.4-2*** below shows graphically the NA and the acceptance cone.

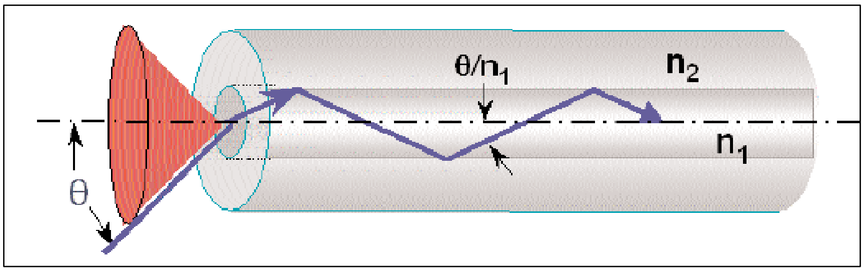



***Figure 3.3.4-2: NA and acceptance cone***

The type (more precisely, their refraction index) of core and cladding materials and the diameter of the core determine the NA and other properties of the FO, and in consequence, the transmission parameters of the system.

Fiber optic size is usually expressed by first giving the core diameter in µm followed by the cladding outer diameter, also in µm. Consequently, 50/125 indicates a core diameter of 50 µm and a cladding diameter of 125 µm, and 9/125 indicates a core diameter of 9 µm and a cladding diameter of 125 µm.

FOs are divided in two mainly groups: Single-mode fibers and multi-mode fibers.

***Single Mode:*** The main difference between the two types of FO is that single-mode fibers (SMF) have a smaller core diameter than multi-mode fibers. The core is so thin (diameter between 8 and 10 µm) that it is in the order of magnitude of the wavelength of light, and therefore geometric optics is not applicable. The light can propagate inside the core only in one way (one mode), minimizing the dispersion of pulses in the output and practically removing jitter in the transmission of logic pulses.

This property is the base of their high bandwidth, making possible their use in high speed & long distance applications.

However these advantages are balanced by some important drawbacks: a thin core has a small NA, and it requires that the transceivers use high precision elements like expensive lasers and connectors, without forgetting elevated intrinsic and installation costs: Splicing is difficult and needs very special tools and highly qualified technicians.

For the above reasons SMFs are deemed not appropriate for a "Tactical" use, and therefore no additional considerations on them will be made in this document.

***Multi Mode*** fibers have a higher core diameter than single-mode fibers allowing that the light propagates inside the core -geometric optics is applicable- by more than one trajectory. This mode of propagation generates more dispersion than single-mode and distorts the logic pulses transmitted across the fiber, having negative repercussions in the distance and bandwidth capabilities.

However, this type of fiber has more Numerical Aperture (NA) than single-mode fibers, permitting higher tolerances in mechanical systems like connectors and even the use of low cost LED transceivers, thus resulting as most suitable for the target system.

***Types of Multi-mode Fibers. Technical Characteristics***
Four main types of multimode fibers are available in the market:

1. **GOF**, with Silica core / Silica cladding (GOF stands for Glass Optical Fiber). Their standard core diameters are 50 and 62,5 μm with 125 μm cladding (50/125 or 62,5/125).
2. Silica core / Polymeric cladding, of which two variants are available:
   a. **PCS** or Plastic Clad Silica, with silica core and silicone cladding. Standard size is 200 μm core with 350 μm cladding (200/350), but a full range of core sizes up to 2000 μm is available on the market.
   b. **HCS** or Hard Clad Silica, with silica core and hard fluorinated polymer cladding. Standard size is 200/230, but a full range of core sizes up to 2000 μm is available in the market.
3. **POF** or Plastic Optic Fibers. There are also two main types of PCS:
   c. The most common one has a 980 μm plastic (Polymethylmethacrylate, PMMA) core surrounded by a hard fluorinated polymer cladding with a total diameter equal to 1000 μm (1 mm), therefore they can be named as 980/1000 fibers.
   d. The newly introduced Graded Index POF, composed of a Graded index plastic core, protected by a PMMA buffer. There are two families of GI-POF, depending on core-cladding material: PMMA based and Perfluorinated polymer based, originally developed by Asahi. There is one standard size of the first type (500/750) and three of the second (200/490, 120/490 and 62.5/250)

Key features of the different candidate fibers are compared in the ***table below***. In it non appropriate fibers are marked in pink, appropriate ones in green and marginally appropriate in yellow. Comments are made in the last column.

***Table 3.3.4-1: Fiber features evaluation***

| Type | Core/Cladding sizes (μm) | Wavelegth (nm) | Attenuation (db/km) | Bandwidth (MHz · km) | Comments |
|---|---|---|---|---|---|
| GOF | 50/125 | 850 | 3.0 | 500 | Small core size for direct use in connectors. May be acceptable with special connection architecture |
| " | 62.5/125 | 850 | 3.5 | 160 | |
| " | 100/125 | 850 | 5.0 | 100 | Small core size, lower bandwidth |
| PCS | 200/350 | 850 | 7 | 20 | Small bandwidth. May be acceptable for short runs (200 m) or low speed (10Base-T) |
| HCS | 200/230 | 850 | 3.5 | 20 | |
| SI-POF | 980/1000 | 650 | 220 | 4 | High attenuation / low bandwidth |
| GI-POF | 500/750 | 850 | 40 | 150-300 | Main drawback is high attenuation |
| " | 200/490 | 850 | 40 | 150-400 | |
| " | 120/490 | 850 | 33 | 188-500 | Attenuation and core size |
| " | 62.5/250 | 850 | 33 | 188-500 | For this core size, GOF is better |

Although there is not a clear winner, finally glass optical fiber was considered as the best compromise solution for the target system, mainly due to high bandwidth, low signal attenuation and low driver power requirements:

- It is capable of getting a complete 100Base-Fx link (more than 1km) without using repeaters.
- Many VCSEL and even low power LED drivers, that reduce the power requirements, are available, keeping the light emitted power below the normative limits (see safety considerations section) also allowing high speeds.
- The price is lower than other fibers with higher core diameters.
- Though it has small core diameter, it allows field mounting connectors with a low cost connectorization kit.

- It has a low numerical aperture (0.2), which gives higher bandwidth.
- A great variety of communication networks use this sort of fiber. The supply is guaranteed.

Nevertheless, if the mechanical and optical requirements in the system connectors are analysed, the use of this type of fiber is not straightforward:

- The small core diameter and the harsh environment operation oblige to use special connectorization techniques.
- Some special connectors exist on the market and could be suitable for this application but they are very expensive and it does not allow be assembled in field.
- The mounting of the connectors, especially if it is made in the field, can be difficult compared with larger core fiber connectorization methods.

***Safety Considerations***

There are some critical safety issues related to use of fiber optic systems in mining environment and it could restrict the types of fibers to being used in the target system. The optical power (especially from high intensity light sources such as lasers) may be a potential source of ignition of methane-air / coal dust mixtures and coal dust layers.

The European Standard - EN 50303 'Group I Category M1 equipment intended to remain functional in atmospheres endangered by firedamp and/or coal dust' defines safe levels for optical radiation by which coal dust/ air-methane mixture may be exposed (in normal/failure conditions):

i) radiated power <150mW or ii) peak radiation flux $<20mW/mm^2$

These values were confirmed by research on 'Laser safety in underground coal mines' carried out by NIOSH with assistance of other independent laboratories (in the UK, Australia and Germany). The research covered defining ignition levels in methane-air mixtures, performed independently by NIOSH (USA), Hills (Australia), PTB (Germany), HSL (UK), as well as coal dust clouds (NIOSH alone).

It was concluded:

- more power is needed to ignite coal dust clouds than is needed to ignite methane-air,
- the amount of laser power needed to create explosions was proportional to the laser beam diameter for the coal dust clouds, as well as for methane-air.

The results suggests that even relatively powerful beams can be used ensuring that the beam diameter is large enough to reduce the beam intensity. The conclusion is illustrated at the ***figure below.*** It shows "ignition curves" of laser power versus beam diameters. To ensure safe operation laser systems should operate well below these ignition curves.

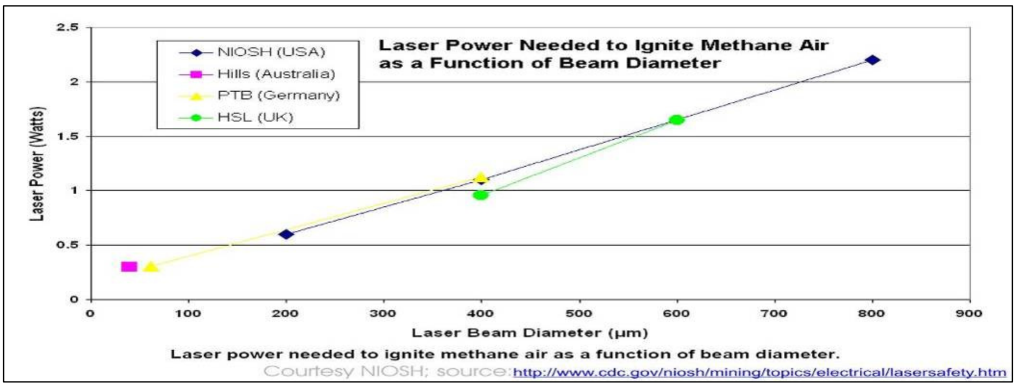



*Figure 3.3.4-3: Laser power vs. beam diameter - ignition curves for methane-air mixture*

However according to the cited above CENELEC EN50303 standard the safety levels cannot be used in case the beam can fall at coal dust layer and cause rise of its temperature above 150°C. The standard suggests carrying out by 'individual tests' as the levels apply only to methane / coal dust – air mixtures. When exposed to high optical radiation the temperature at the surface rise and can be a source of ignition. It might be a coal dust layer as well as iron oxide or other absorbing surfaces. In case of very small radiating areas like broken dirty fibre optic cables the level of power density needed to cause ignition is much higher than at larger apertures. The results of EU supported research carried out by PTB (Germany) with their UK and French partners resulted in draft for European and international standards where safety levels were defined to be:

i) radiated power <35mW or ii) peak radiation flux $<5mW/mm^2$

As compared to the safety levels for air-methane/ coal dust mixtures these levels are much constraining the allowable power for laser light sources.

A very important question identified during the study is reliable means of limiting the radiated power. The EN 50303 standard defines allowable ways to do it:

- can be 'limited by infallible energy source',
- by use of 'infallible limiting device',
- by means of interlock which would switch off the transmitter in case the FO connection breaks.

There is also another method – not explicitly defined by EN50303 standard but found practical by most researchers from NIOSH. Namely it is the optical fuse that limits the power in time shorter than ignition delay and hence the ignition.

A question arise - which practical implementations are found acceptable across different European notified bodies? From the information exchanged among the partners a conclusion can be concluded that the easiest way is limiting the electrical power. Optical fuses were found an uncommon protection mean for mining optical systems. No indication of practical use of such type of protection, as well as unknown chances for getting ATEX approval gave caused the research to focus on electrical power limiting protection type.

Moreover, what is known from experience with Polish notified bodies indicates they are more likely to approve solutions based on LED transmitters than lasers. For the latter it is hard to prove explosion safety in case of electronic protection means. On the other hand, the protection circuits in most cases can drastically affect the performance in terms of limiting the range. These factors were taken into consideration in the development work carried out in following tasks.

***Conclusions***

When evaluating the pros and cons of all selected kinds of fibers, the relation between the type of fiber and the connector development, in addition to other factors like power requirements and cost was clear.

The main advantages of POF are the easy connectorization, fast installation and low tools cost, though the bandwidth is very limited, being not enough for establishing a 100Base-FX link. Silica core fibers (HCS and GOF) have sufficient bandwidth for fast Ethernet, however the HCS bandwidth distance product is just below the limit.

A new connectorization system must be designed for any type of fibers, but there are differences between plastic and silica core fibers. If the connectorization method includes optical elements, the small diameter silica core of both HCS and GOF must be protected with a glass (or similar material) and the light must be somehow manipulated (collimated, focused) in order to be feed into the fibre. In the case of POF fiber, manipulating the light beam is not required because its diameter is large enough to not being affected by dust [possibly] deposited in the light path.

Both electrical and light power of the fiber drivers is a very important factor since big differences between drivers of each type of fiber have been observed. The numerical aperture is one of the factors that determine the quantity of light that must be inserted into the fiber. GOF fibers have the lower numerical aperture, so it is the type that theoretically needs the drivers with lower power.

Since GOF fibers presents the best features in terms of bandwidth, power and cost and, in any case a new connector must be designed for any type of fiber, it was decided to use this silica fiber. However, the development of the connector, especially if it includes light processing, will be more complex than for any other fibers, due to the small -50µm- core size, which will require smaller manufacturing tolerances in order to obtain a proper centring and axis aligning.

In despite of this, GOF is still the most appropriate fiber for the target design, and the efforts in the successive task are centred in the design of a connector for this type of fiber.

### 3.3.4.2 Connector and Cabling development

***Fiber Contact Development***

One of the weak points in a wired up system is the bus connections or contact points, especially when it can be disconnected and reconnected a lot of times in a harsh environment.

Robust versions of the connectors more commonly used in conventional fiber networks exist on the market but they are not appropriate to the system because it does not implement any method for protecting the fiber core of external agents when it is not mated. Although some harsh environment connector manufacturers offer solutions for industrial, military or aerospace applications, its high cost and the assembly in factory without possibilities of making field installations or repairing, make its use impossible in the target system.

As a result of the impossibility of using a commercial connector, a new one was developed specially adapted for underground use.

The design of a connector for the target system is a task highly related with the type of the fiber used in the network. Various connectorization techniques were studied for analyzing the advantages as well as the development time, cost, power supplies and manufacturing requirements. Finally the implementation of a beam expander into the contacts was selected as the most suitable.

***Optical Beam Expander***

This method is based on transferring the light between contacts increasing the original light beam diameter using a lens system. Using a fiber with a small core diameter requires also that the lens arrangement have provisions for preserving both the core and the light beam from external influences and damage, for example dust or damages in the handling process.

The effect of a beam expander (illustrated in the ***figure below***) between two connectors is increasing the diameter of the light beam when going out of the transmitting "pin" and then reducing (focusing) it for its launching in the outgoing fiber situated in the another connector.

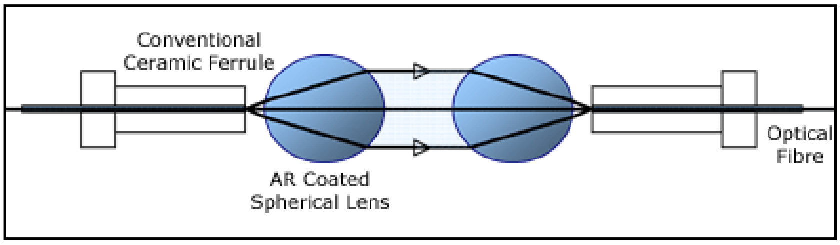



***Figure 3.3.4-4: Beam Expander schematic***

The use of this technology has the following features:

- Increases the beam diameter in the exposed part and the influence of any dust particle in the light path is minimized because the shadow of the particle is very small compared with the area of the light spot. If the direct light transference were made with a small core fiber, a dust mote could obstruct totally the light.
- Multiplies the alignment tolerances between the fibers. This is an important factor because the alignment of two fibers directly (without any optical treatment) requires an accuracy of few µm.
- Protects the fiber core of external aggressions since the only part exposed to the environment is the ball lens and the use of scratch-resistant materials like sapphire or ruby allows that the cleaning process can be done with a simple cloth.

Once the method to develop the fiber contact was selected, an in-depth assessment from the point of view of the physical implementation must be performed in order to determine whether the development of the "fibre optic contact" was feasible. The main problem of implementing a beam expander for a fiber optic with only some µm of core diameter is the low mechanical tolerances allowable during the manufacturing process. In order to get an approximation of these mechanical deviations limits, a software simulator was developed. This application allows to know the light beam trajectory in function of several parameters of the different parts of the fiber contact, as for example, lens diameter, lens material reflection index, deviation of the lens respect to the fiber, deviation and distance between two fiber contacts, etc., quantifying the allowable mechanical errors during the manufacturing process in function of the type of elements used in the design.

After performing a search of the kind of lens materials available on the market for similar applications, finally the sapphire was selected as the most suitable one. This almost transparent material has excellent properties in harsh environments. It is strong and hard, as well as supports easily chemical aggressions and it is less expensive than others options. The refraction index is 1.768 but its transmission coefficient is only 80%. Nevertheless, this loss is approximately 2dB, which is in the range of the tolerable limits. The lens size was selected based on the standard ST ferule diameter, i.e. 2.5mm. Explained later, this fact will make possible to use a commercial 2.5mm ferrule as coupling element between the fiber and the rest of the parts of the contact. Finally the following table shows an estimation of the manufacturing tolerances based on 50/125 µm multimode GOF and 2.5mm diameter sapphire ball lens.

***Table 3.3.4-2: Tolerances of manufacture for 50/125µm fiber, 2.5mm sapphire beam expander***

| Magnitude | Nominal value | Tolerance |
|---|---|---|
| Distance from fiber to lens | 187µm | +-20 µm |
| Alignment between fiber and lens | 0 | +-5 µm |
| Distance between lenses | 500 µm | -300 µm / +2000 µm |
| Alignment between expanders | 0 | +-100 µm |

Some tests of the concept were carried out in the labs before building the parts of the contact. The ***figure below*** shows a practical demonstration of the beam expander method. Using elements in a bigger scale and ruby instead of sapphire lens for making easier the parts handling, the outgoing light from a fiber core, can be collimated just placing the fiber end in the ball lens focal point.

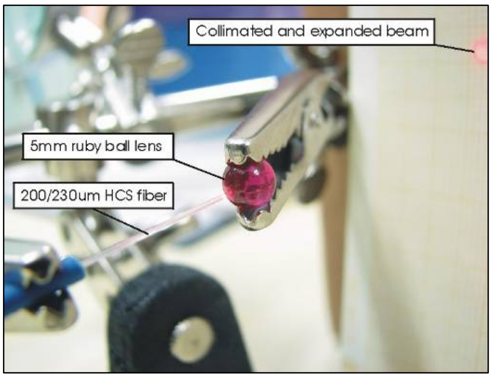



***Figure 3.3.4-5: Beam collimator principle lab test***

***Fiber Contact Design***

To put the theoretical research and modelling into practice and reach the goals established for the target application, a custom-built fiber contact was designed resolving various problems as field-mounting, low cost or ball expander integration. According to the ***table 3.3.4-2***, the main difficulty from the mechanic point of view is the alignment between fiber and ball lens as well as the space between the lens and the fiber, which must be equal to the focal distance of the ball. The design is based in an adaptor or an extension which is added to a modified ST ferrule and it is used to hold down all parts of the contact together and correctly positioned. The design uses the ferrule as a guide for the rest of the parts so it must have a high mechanical precision because it is the base of the beam expander optical alignment.

*Figure 3.3.4-6: 3D model of the fiber contact design. Parts position (up) and assembled (down)*

In view of the impossibility of getting commercial parts for manufacturing the whole contact, some elements of the first prototypes were made in the lab workshop using a lathe and hand tools. Although this technique is not the most suitable one, especially from the point of view of manufacturing costs, it helps to refine weak points in the original design, adjusting critical parts and assessing the influence of the mechanical tolerances in the final performance of the design. On the other hand, the parts made using this hand technique, i.e. turning and tapering the ferrule, machining the shell and specially the spacer, requires multiple testing and measuring, discarding many out of tolerance parts, and spending a great deal of time to get just a couple of elements within the tolerances set in ***table 3.3.4-2, page 69.***

***Contact Design Test***

Using an optic signal meter system, the amount of light transferred from one contact to another can be measured. With these tools the contacts' misalignment when they are assembled into the final connector can be simulated, establishing design requirements for the connector socket manufacturing process and assessing the advantages provided by the new design respect to the standard contacts as far as mechanical misalignment tolerances is concerned. During the testing process, one of the contacts is held on a fixed platform while the other is mounted on the 3D micro translation stage. The same tests were carried out using 3 pairs of standard ST fiber contacts and 1 pair of prototypes of contacts with beam expander. ***Figure 3.3.4-7*** shows the results of the tests.

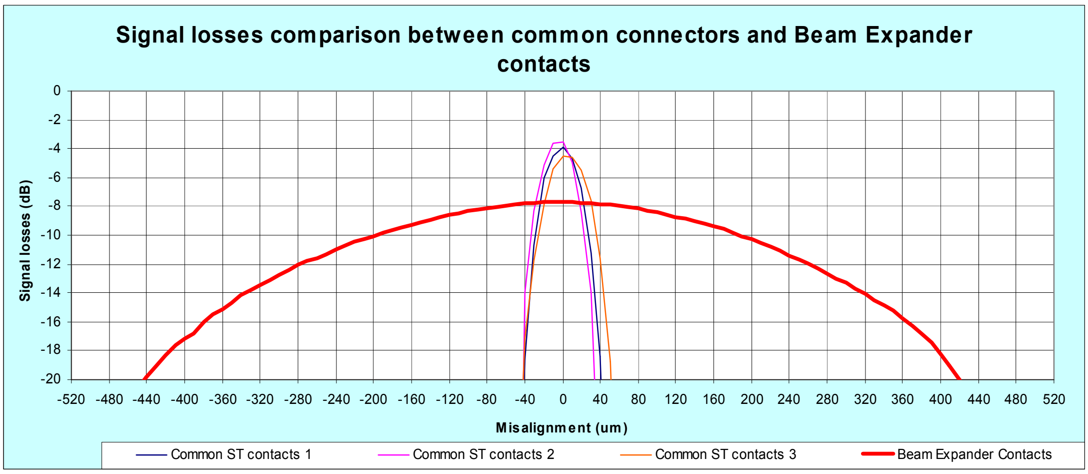



*Figure 3.3.4-7: Signal loss comparison. Initial tests*

Analysing the above picture, it can be observed that the fibers faced directly by ST connectors have a high sensibility to the fiber axes deviation compared with a couple of contacts with beam expander in the same conditions. If a signal losses of -20dB is set as a limit value, the directly faced fibers allow only a 10% of alignment error compared with the fibers faced through beam expander. Also another factor improved by the design is the tolerance in the distance between fibers. The fibers faced with common ST connectors have high signal losses (unacceptable for the transceivers) when the contacts are not almost in contact between them (the maximums allowable separation is around 10 µm). On the other hand, the beam expander contacts can be separated even various hundred of µm without having high loss levels. During the test, the lenses have been separated up to 500 µm and the losses caused by this distance increase were only 3 dB.

In the results shown on ***figure 3.3.4-7,*** a small offset in the signal losses can be observed. The lower attenuation for ST ferrules appears at 3.5dB. That is too high for this kind of contacts, being the nominal signal losses 0.2 or 0.3 dB approx. Further tests were performed after some mechanical adjustments and measurement equipment calibration, getting the same curve pattern than reported but reducing the minimum signal attenuation to 0.4 dB for standard ST ferrules and 2.8 dB for the contacts with beam expander (it is close to the theoretical limit imposed by the aforementioned light transmittability of the sapphire).

***Mixed Connector Development***

The contact including the beam expander system was to be housed into a socket in a multiple pin connector designed for the fieldbus architectures, with the objective of implementing a multiple connector with fiber and copper contacts. It was also desirable for the fiber and copper contacts to be interchangeable. The count of the contacts needed in the fieldbus connector is shown in ***table 3.3.4-3.***

***Table 3.3.4-3: Field bus connector pin count***

| Number | Function | Type |
|---|---|---|
| 1 | power supply (+) | copper |
| 2 | power supply (-) | copper |
| 3 | analog/Digital differential communication (+) | copper |
| 4 | analog/Digital differential communication (-) | copper |
| 5 | fiber bus TX | fiber |
| 6 | fiber bus RX | fiber |
| 7 | extra bus | fiber or copper |
| 8 | extra bus | fiber or copper |
| 9 | emergency stop | copper |

The solution proposed by a connector's manufacturer (ICP) is a design with nine pins inserted into a socket with a total external socket diameter of 30mm. The slot prepared for each pin has a diameter of 5mm and it allows the assembly of an electrical contact with 3 mm of external diameter in the male part. The group of the contacts mounted in the socket will be enclosed by a stainless steel shell for providing toughness and environmental protection. After performing various prototypes and including some improvements to the original design, one of the first operational prototypes are shown in the ***figure 3.3.4-8.***

***Figure 3.3.4-8: Male (left) and female (right) mixed sockets (the two fiber slots are marked with 'O').***

***Mixed Cable Development***

Before producing a sort of new cable, especially for custom-built cables, the manufacturer needs detailed information about the desired cable properties. The definition of the technical specification of a cable for mining use requires a detail analysis of the materials used on it in order to get a final product capable of satisfying the physical, electrical and environmental needs of the underground applications.
In a system based on fieldbus communication where the power supply, digital data communication and analog signals are enclosed by the same jacket, an individually analysis of each wire must be carried out both to assure the own line functionality and avoid the interference with others.

In the case of the power lines, the low electrical resistance of the copper wires is one of the most important parameters to take into account due to the cable is usually installed along hundreds of meters and an important resistance of the conductors could cause a significant voltage drop between the power supply output and the device to be powered. This factor can be improved increasing the conductor section, however it has another side effects, for example, the inductance to resistance ratio ($L_o/R_o$) is also increased, and consequently it means a limitation of cable length, as well as to the elements (number or/and type) to be inserted into the fieldbus. The use of wires with a greater section also implies a reduction of the bending diameter of the cable, but possibly, the worst effect is an increase of the tension in the thin copper strands whose compose the conductor, becoming to the cable more vulnerable to the fatigue.

The data lines for fieldbus based applications are usually twisted pairs due to the most of the standards used in this sort of systems for digital communications are based on differential mode signals (e.g. RS485). This form of wiring is also applicable to the analog voice communication pairs; however, the use of two kinds of lines (data and voice) in the same cable requires the use of shielded twisted pairs correctly grounded, especially to avoid the interference of the square pulses of the digital signal into the analog voice signal.

One of the weak points of the cables is the working tension. For the target cable, the estimated tensile strength of the total copper conductors is around 9000N, nevertheless, the use of fiber optic in mixed cables implies a huge limitation of the cable strength. Most of the fiber cables used for outdoor installations dot not support more than 4500N even using rugged aramide (Kevlar) yarn reinforcement. However the use of high resistant jackets means a bigger external diameter of the fiber cable and consequently, of the total mixed cable as well, increasing the weight, the minimum bending diameter and, usually, the cable cost.

For a mixed cable, the distribution of the elements (optical and electrical) through the cable section will be a vital factor, mainly to avoid a compression or stretching of the weak fibers by the high diameter copper wires used for power supply. This crushing will be especially important in sharp bends, where, when added to the internal tension, it could cause a breakage in the glass fiber core or a premature stress fracture. As a good pattern, a symmetric distribution keeping the fibers as close as possible to the radial axis should minimize the tension endured by the weak glass fiber in the curves.

The selection of a suitable jacket material helps to reduce the tension strength in the internal wires and fibers. One of the commonly used for mining cables is PVC (Polyvinyl Chloride). It gives high flexibility to the cable, reducing both the conductor tension and the minimum bending diameter.

PVC presents a good waterproofing, but it can be vulnerable to oil or fuel, although the fieldbuses applied to control and monitoring system are not usually in contact with these short of fluids. Sometimes PVC is modified adding CPE (Chlorinated Polyethylene) to improve the robustness. The result is a flexible thermoplastic with high tear strength, good chemical resistance and inherently difficult to ignite.

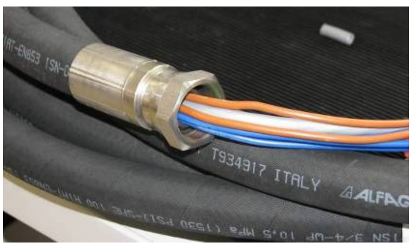
According to the above, there are several parameters to be defined in advance to the cable manufacturing process. This process, especially for custom-built cables generates high initial costs and the minimum order to be manufactured usually is a several kilometers spool. Due to this fact, a prototype of mixed cable was prepared in the labs, mainly for mechanical testing (bend radius, tensile strength in curves, etc.).

***Prototype Construction***

The prototype consists basically of a high resistant jacket with fiber and copper wired inserted on it. The jacket is based on a hydraulic hose made of synthetic rubber resistant to abrasion and hydrocarbon. The tube is reinforced with a high tensile steel braid and it is suitable for -40ºC to +80ºC working temperature. The use of a steel armoured jacket provides an extra electrical shield for the internal conductors (if it is correctly grounded).

With an internal diameter of 19mm, the distribution of the copper wires and fiber optics can be changed easily to perform various mechanical tests and the fibers can be replaced in case of core breakage.

***Figure 3.3.4-9*** below shows the mixed cable (unconnectored) with all the internal elements:



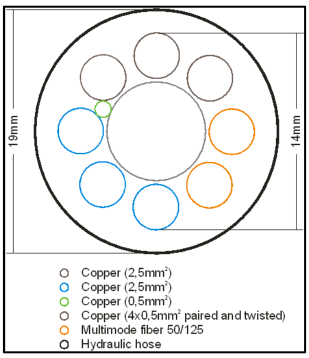




***Figure 3.3.4-9: Mixed cable jacket and internal electrical and optical conductors (left); wires distribution detail (right).***

The coupling between the connector body and the cable has been performed by means of a modified RELIA-2000 connector cover. The modification implies to make a coupling thread on the backshell surface to be mounted into the hose assembly element. Both parts are made of stainless steel.

#### 3.3.4.3 Interfaces development

The work performed in this task was divided in two different developments;

- a universal fiber optic interface for tactical applications and
- a fiber optic device for trunks communication fiber using WDM technology.

***Universal FO Interface for Tactical Applications***

Two design lines were initially considered for implementing a universal fiber optic device aimed for tactical applications. The first one, and also the most interesting for multiple reasons, was the development of the interface from the electronic design basis. It would lead to a directly certifiable product, for the electronic would be designed according to the ATEX rules (intrinsically safe), in a small size enclosure, having a low power consumption and all the functionalities that a modern mining exploitation requires from the point of view of expandability, connectivity, interfaces (wide range of physical and protocol allowed), etc. However, after performing a detailed analysis of the needed elements to make up the apparatus and specially the development times for hardware and software implementation, this approach was discarded. The complexity of the hardware, relative high amount of resources for software development and the continuous evolution of this kind of products (in essence is a device aimed for IT installed in a special environment) tipped the scales in favour of the second implementation method; the adaptation of commercial devices.

The alternative to make a new media converter is the use of a commercial device (or a group of devices) and adapt it for being used in underground work conditions, from both electrical and physical points of view.

A great amount of Ethernet 100Base-Fx communication devices are available on the market, most of them use standard connectors (ST, SC, etc.). 100Base-Fx to 10/100Base-Tx is the common and almost the only media conversion done. Since our system needs a multi port and multi protocol media conversion, the apparatus must be composed of more than one single device. Most of the efforts have been focused on the media converter, which is the core of the universal interface. The rest of "peripherals" are connected to it using a standard Ethernet copper port and a wide range of products can be found on the market for most of the applications (WiFi access points, PAN bridges, RS485 transceivers, etc.). After performing an analysis of the media converters aimed for industrial applications available on the market, finally a model from Moxa manufacturer was chosen. The EDS-5XXA and EDS-4XXA series fulfil the requirements of the target design from the points of view of functionality, application and ATEX adaptation; up to 16 Ethernet ports (including the 2 fiber ports), local and remotely managed switch using TelNet, web browser and SNMP management, multi-protocol redundancy management using STP, RSTP and proprietary methods, isolated digital inputs and outputs and a fiber link budget of 12dB, suitable for supporting the signal losses of the beam expander contacts or even the series connection of more than one mixed cable segment.

From the point of view of the ATEX adaptation, a detailed electronic analysis was performed for converting the circuitry into intrinsically safe (i.e. "i" protection mode) so the next issues were analyzed (please refer to Deliverable D4.1 report for further details):

- Voltage and current requirements
- Power dissipation
- Ethernet coupling line parameters

***Figure 3.3.4-10, next page*** shows a block diagram of the critical elements distribution.

After performing the analysis a media converter was modified removing the switched regulators, reducing the maximum dissipated power in case of failure and inserting limiting elements in the copper Ethernet interface. An external intrinsically safe power supply was used to power the circuitry of the media converter as well as the peripherals ***(figure 3.3.4-11).*** This topology requires a "d" protection mode enclosure only for the power supply and a light and inexpensive enclosure for the interface itself.

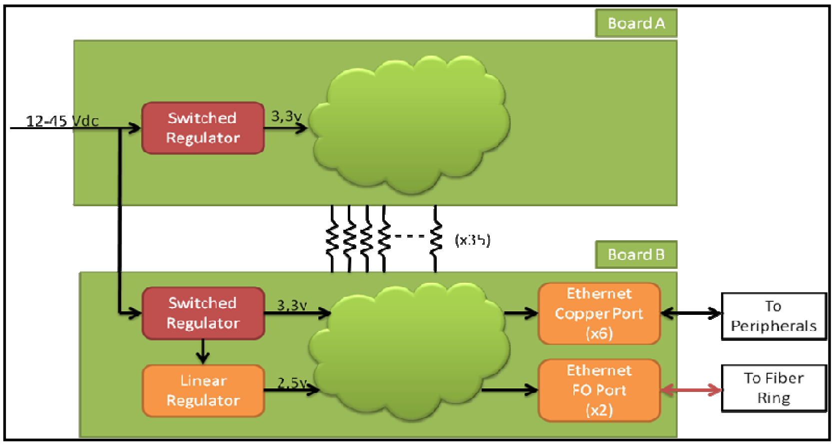



***Figure 3.3.4-10: Key parts to be modified in order to become intrinsically safe the commercial circuitry***

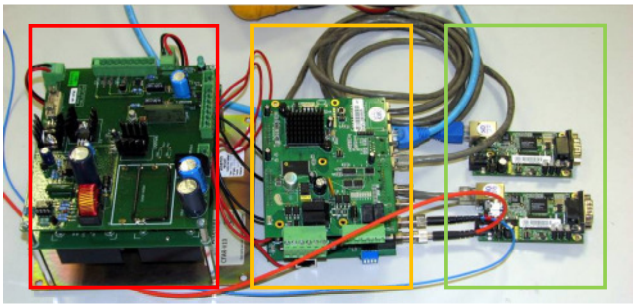


***Figure 3.3.4-11: Intrinsically safe power supply (red), media converter (orange) and Ethernet to RS485 interfaces (green).***

In order to proceed to certify this media converter, conversations with both the notified body and design department of Moxa were maintained with positive collaboration of the two parts. The final certificate of the product is expected to be obtained few months after the end of the project.

***Trunk fiber interface using WDM technology***

State of the art solution for WDM technology was chosen as a base for development of explosion proof fibre optic access point/media converter aimed for trunk communication lines based on single mode fiber (non tactical applications). The WDM technology enables full-duplex transmission using only single optical fibre. Therefore it has an advantage of doubling the capacity of existing cable infrastructure or enabling redundancy at no additional cabling cost. The principle of operation (***figure 3.3.4-12***) is based on transmission over two different wavelengths hence the name.

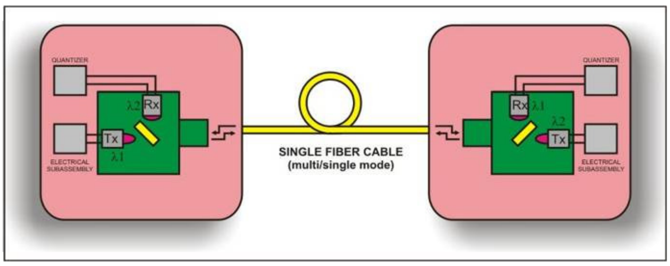



***Figure 3.3.4-12: WDM technology (a)-the principle (b) first developed interface***

Positive results obtained during the tests of first developed WDM interfaces as well as analysis of explosion protection means (enabling safely limit energy in failure modes) encouraged further development of interconnection interfaces. In the next step the versatile interface device functioning as media converter/access device (dubbed µZIST) has been developed. It makes possible connection of standard based client devices through serial interfaces (RS485/422), optical fibre interfaces Ethernet 10/100 Base-FX or copper based Ethernet 10/100 Base-TX to the optical single strand backbone employing WDM technology. A few concepts were studied. The final relayed on standard-based solution taking advantage of software routing and ASIC based packet switching. Schematic diagram representing logical connections between basic blocks of FO access point is shown in the ***figure 3.3.4-13.***

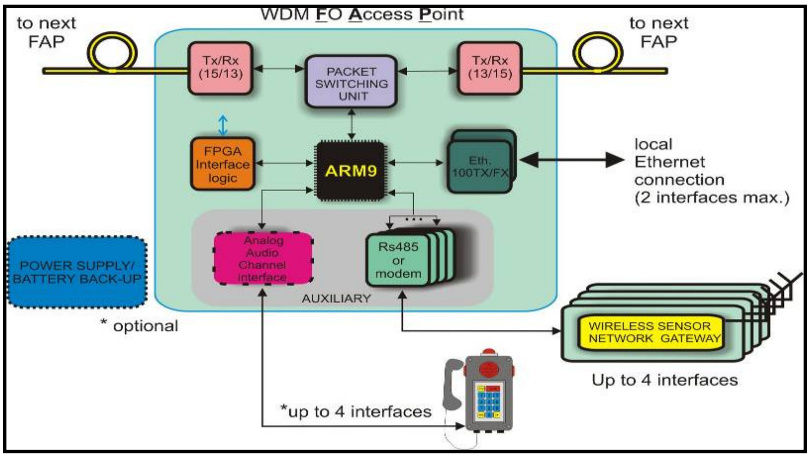



***Figure 3.3.4-13: WDM Fibre optical interface/access point - schematic diagram***

The main building blocks of the media converter include:

- FO transmission module,
- packet switching module (based on ASIC and low power FPGA logic),
- peripheral rich MCU (ARM9),
- interface modules

The FO transmission module employs two FO WDM single strand interfaces to enable operation in ring topology. The packet switching module synchronizes the transmission and provides data path to the microcontroller. The MCU unit runs under control of embedded Linux operating system. Transfer of data to the interface modules is possible with use of low voltage SPI, USART, I2S or Ethernet MII interfaces. The first main module (dubbed µZIST-FSE) was designed, fabricated and tested to ensure the basic functionality ***(figure 3.3.4-14).***

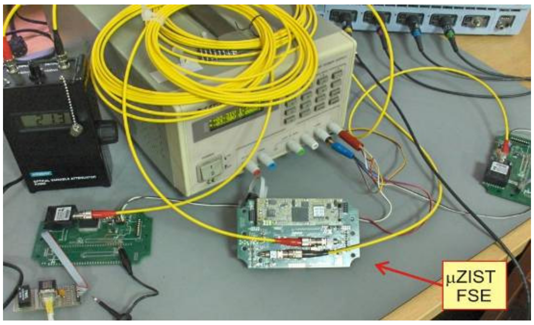



***Figure 3.3.4-14: Tests of first revision of the FO WDM access point modules***

The test results indicated good performance of WDM communication link. The achieved results during the tests with optical attenuator showed the devices should be able to communicate at full speed at least to the distance above 30km.
The µZIST-FSE is capable to operate with two WDM interfaces simultaneously (important to realise ring topology transmission scheme) and up to two Ethernet interfaces (Ethernet 100Base Fx/Tx) are available at the module to make possible branching from the transmission trunk.
With regard to auxiliary interfaces the development work was focused on the explosion proof serial interfaces (RS485/422) necessary to ensure connectivity with the wireless gateway for sensor access. The developed module (dubbed µZIST-RS4) allows to connect up to 4 serial devices with the connection speed up to 2Mb/s. It was decided the device will be housed in environmentally protected alloy enclosures and the auxiliary serial fieldbus interface modules will be integrated in a separate box of the enclosure. The complete µZIST station contains also the power regulator module which produces the required stabilised and energy limited supply voltages for digital logic. The prototype µZIST stations were assembled and tested (***figure 3.3.4-15***) prior to the underground tests in Guido mine carried out in WP5.

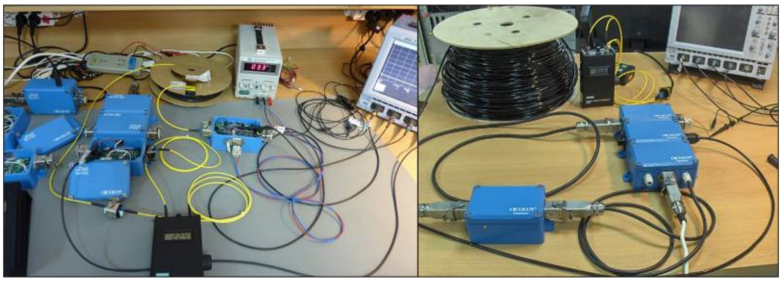


*Figure 3.3.4-15: First revision of the FO WDM access point modules – being checked before test installation*

For the test configuration three µZIST stations (***figure 3.3.4-16***) were connected together with single mode optical fibre WDM connection and installed in Guido mine Zabrze, Poland (see further details in WP5 description). It was initially planned that tests with the tactical type beam-expanding connectors will also be carried out within this installation as a part of cooperative activities with AITEMIN. For that purpose a version with capability to connect multimode optical interface was prepared, acting as a bridge between trunk and tactical FO systems. These tests however, have not been conducted due to the connector manufacturer, ICP, who was cooperating with AITEMIN stopped business and closed the factory due to the current financial crisis. Currently a search looking for another manufacturer capable of producing a mixed connector batch is being conducted, with the target of completing the integration tests and commercialize the product.

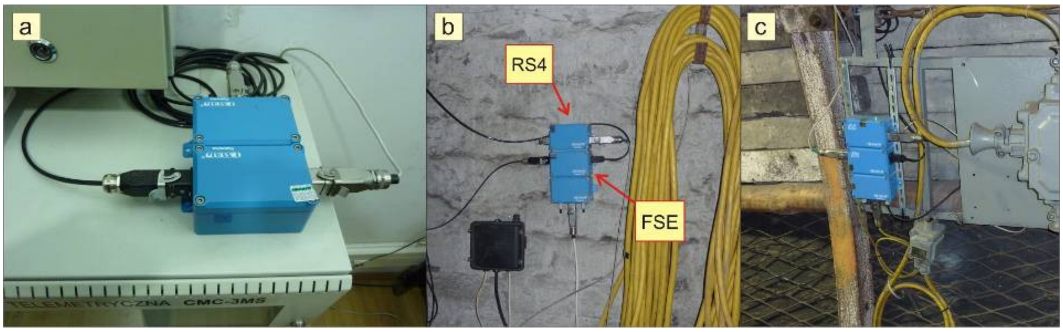



*Figure 3.3.4-16: FO WDM access point modules – installed in Guido mine*

### 3.3.4.4 Software development

For the trunk fiber devices developed with WDM, the required embedded control software was developed. It performs the configuration and supervision tasks as well as enables configuration of serial auxiliary interfaces and IP connectivity settings.

In case of the tactical fiber devices where the configuration changes, diagnostic procedures, etc. are done more frequently and the managing software requires more power over the device, the use of a commercial media converter as a core of the universal fiber interface, reduces the software development times due to the internal microprocessors/controllers include the software (firmware) needed for performing all the device functionality. In addition, the use of a device aimed for industrial application is already equipped with mechanisms and procedures to allow a smooth running of an industrial installation as the target application, including diagnostics functions and configurable alerts trigger by power failures, communication interruptions, etc.

Once a solid firmware is implemented in the devices, this task was reoriented towards the analysis of the device/network configuration techniques; i.e., in short, how the device parameters can be remotely accessed from the SCADA. For the selected device, it is not only limited to the basic Ethernet network configuration parameters, abovementioned utilities for network monitoring and administration functions have been also implemented into the firmware.

Two ways to get remote access to the device parameters are given by the manufacturer. They are via HTTP and TelNet console. HTTP allows a graphical interface using any standard web browser, with the capability of monitoring and modifying the internal media converter parameters including network traffic priority, basis network configuration, alarm triggers, etc. TelNet offers to do the same but it uses a basic interface over a text console instead of a graphical screen. However, although these two methods where initially considered to access to the device, finally were discarded due to they are suitable for setting up a single interface, but not for accessing easily to several devices connected to the same network and have a global vision of the installation communication system.

Hence, an independent software for monitoring and changing the parameters of network interfaces was developed within WP4. The software is based on Simple Network Management Protocol (SNMP), which is currently the standard tool used by computer network administrators. It was written in C# language which enables its platform independent use.

The SNMP protocol was developed as the standard tool for the management of different parts of telecommunication network like routers, switches, computer or telephone exchanges. The protocol is based on two types of software: the manager SNMP and the agent SNMP. Both manager SNMP and agent SNMP have to be equipped with a list of parameters which they can exchange with each other. For that purpose, each manufacturer of network devices prepares SNMP database. The database is a textual file with a list of parameters and their description. The file has a name of device's MIB (Management Information Database). ***Figure 3.3.4-17*** below shows a part of MIB describing a group *swMgmt* for *Moxa Ether Device Switch EDS508A.*

```
-- -------------------------------------------------------------
-- swMgmt group
-- -------------------------------------------------------------

   numberOfPorts OBJECT-TYPE
       SYNTAX INTEGER
       MAX-ACCESS read-only
       STATUS current
       DESCRIPTION
           "Total Ports."
       ::= {swMgmt 1}

   switchModel OBJECT-TYPE
       SYNTAX DisplayString
       MAX-ACCESS read-only
       STATUS current
       DESCRIPTION
           "The switch model."
       ::= { swMgmt 2 }
```

***Figure 3.3.4-17: Part of MIB database***

The main screen of the application is shown in ***figure 3.3.4-18***:

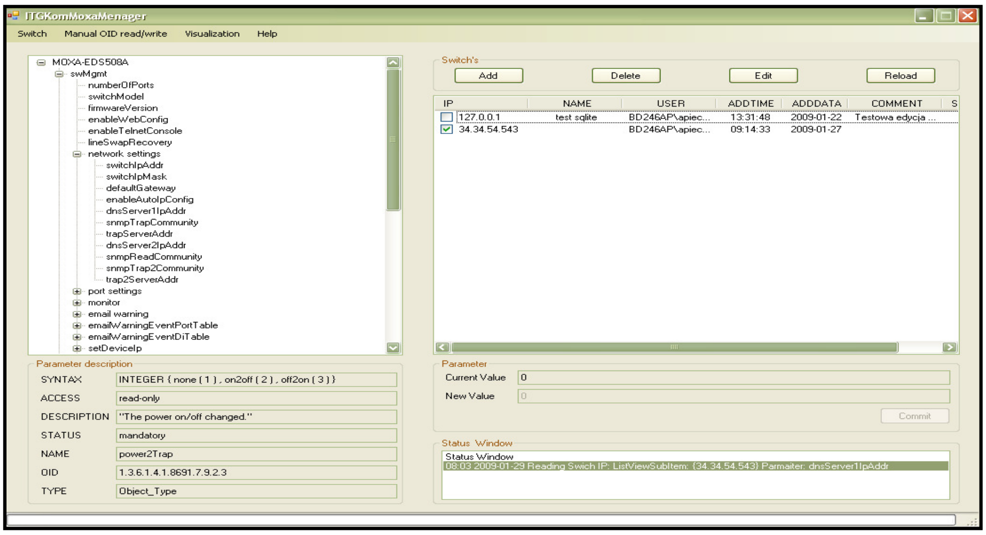



***Figure 3.3.4-18: Main screen of the management software***

### 3.3.5 Underground testing (WP5)

#### 3.3.5.1 Field Tests of Databus system

***Tactical communication system based on fiber optic.***
According to the project plan activities, the trials of the tactical communication system based on fiber optic were performed at "Fundación Santa Bárbara" facilities, located in León (north of Spain).The test scenario consists of two longwalls (***figure 3.3.5.1***), a bypass tunnel between them and a control room located 500 meters from the longwalls entrances.

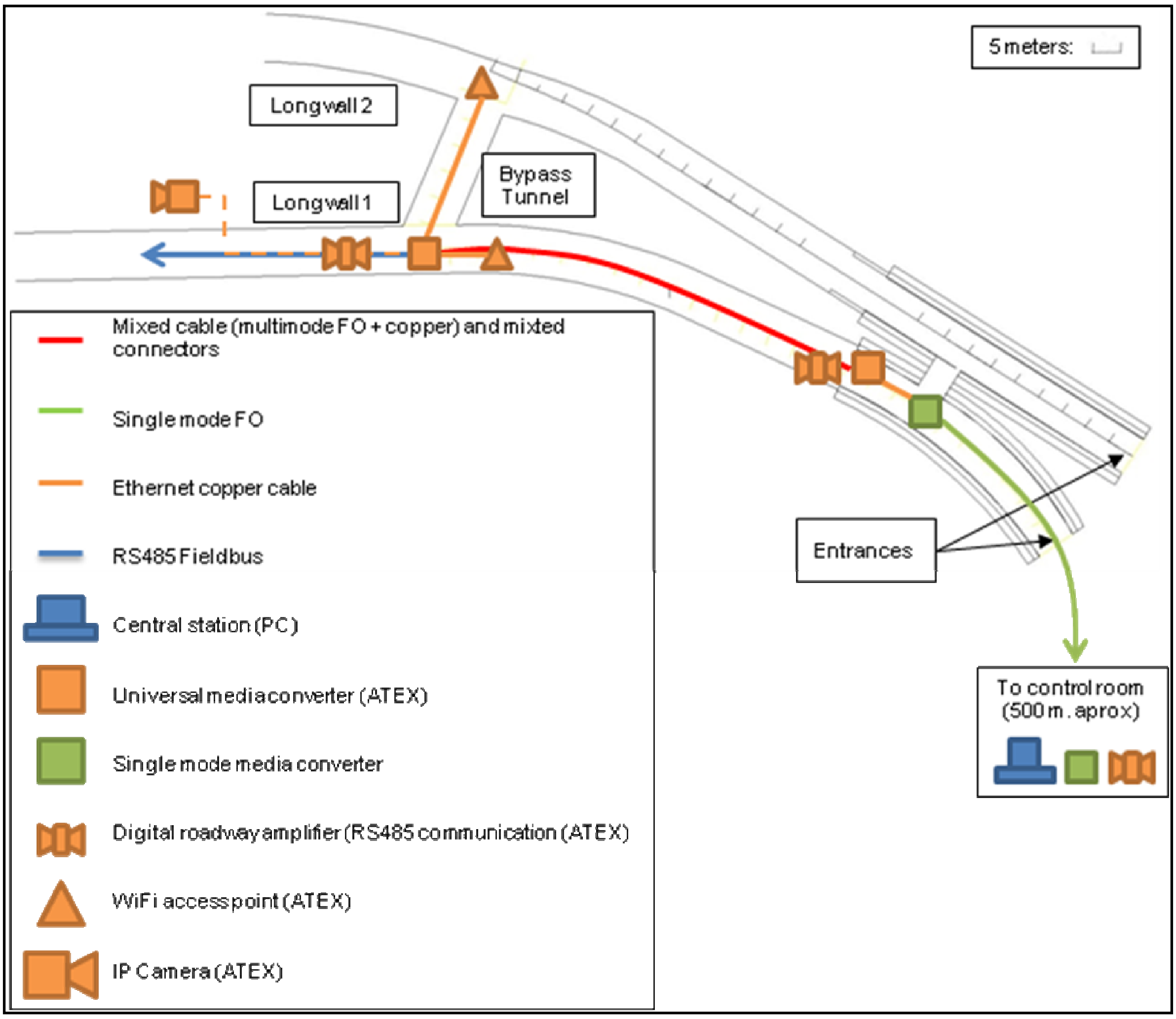



***Figure 3.3.5-1: Trials scenario map, communication network structure and devices distribution***

Before the new communication system based on FO was installed, the communications between the different electronic systems distributed along in the mine (e.g. environmental control, ventilation regulation, voice communication, etc.) were based on RS-485 lines for digital systems and twisted pair for speech communications (analog). The main problems encountered using these techniques were the low speed rates through the fieldbuses and the high background noise level existing during the voice communications. The communication between the underground area and the control room was already performed using a conventional single mode fiber optic installed form the offices to close to the longwalls entrances, however it was used for another purposes (not for mine parameters controlling/monitoring) due to these kind of standard FO systems are not suitable to be used in harsh environments conditions as required inside the mine.

The installation of the system developed during the project should solve the above mentioned problems using FO as transmission media along the longwalls, integrating into it the existing monitoring and control systems (including speech communications) and connecting the new tactical fiber optic system to the existing trunk fiber line (single mode). In addition, the new system will be capable of integrating future services under the same tactical network (e.g. digital video inside the mine just in the development face using ATEX IP cameras).

During the trials the next elements developed during the project were used ***(figure 3.3.5-2)***:

- Fiber optic contacts assembled and integrated into the mixed connectors (male).
- Mixed cable including copper and optic wires as well as mixed connector (female).
- Prototype of universal media converter including mixed connectors and Ethernet (copper and optical), ZigBee and RS485 connectivity.

***Figure 3.3.5-2: From left to right; i) mixed connector (male), ii) mixed connector (female) including mixed cable and iii) universal media converter prototype***

During the tests, the devices were placed and connected according to the structure shown on ***figure 3.3.5-1***, previous page. The original high speed network, only consisting of a link between the tunnel entrance and the offices, was extended along one of the longwall using the tactical system capable of withstanding the harsh conditions inside the mine.

Once the Ethernet network was installed and the universal media converters became operative, some peripherals were connected to them. The firsts were various roadway amplifiers based on digital voice communication. These devices, partially developed under the RAINOW project are capable of establishing speech communication using wireless headsets based on Bluetooth and transfer the voice information to a fieldbus in a digital format. They are also capable of digitalize analog voice using its built-in microphone and vice-versa, reproduce the sound received from the fieldbus in digital mode through its speakers.

In addition two WiFi access points were installed, allowing the integration into the network of every control system or device based on the standard IEEE 802.11b/g. Finally, and used only during the trials, an IP camera was connected to the network in order to both test the system using a service with a great bandwidth requirement (i.e. the transmission of digital video in real time) and, using this video images, monitoring the development of the tests of a new shot concrete method from the control room.
During the trials the next points were tested, obtaining positive results in all of them:

- The background noise of the voice communication was (practically) removed because of the use of digital roadway amplifiers in combination with a network capable of providing the bandwidth required for it.
- The tactical FO system could be easily integrated with the existing communication network (a trunk single mode fiber in this case) using a standard Ethernet port (copper).
- WiFi access points and an IP video camera could be easily integrated into the tactical system.

Due to the signal modulation philosophy of an Ethernet based communication (both in FX and TX modes) when a link between two devices is established, it means to get up to 100Mbps of bandwidth independently of the signal losses along the transmission media. It means that the attenuation of the fiber contacts or the fiber optic itself do not reduces the allowable bandwidth (this fact happens in other communication methods as RS485, where a non correctly done installation can works well at low baud rates and fails when the data transfer speed is increased). This fact has been proved installing at once the digital IP camera and the digital roadway amplifiers, without observing substantial delays in neither of the two services.

However, during the course of the trials some communication problems were found in relation to the Ethernet copper ports. Despite of RJ45 sockets with a IP67 protection grade were installed on the universal media converter case for the Ethernet copper ports, the handling of the connectors in the dirty mine environment caused some contact failures and communication interruptions between the media converter and peripherals. This fact must be taken into account in order to perform future researches to develop an Ethernet connector suitable for mining applications.

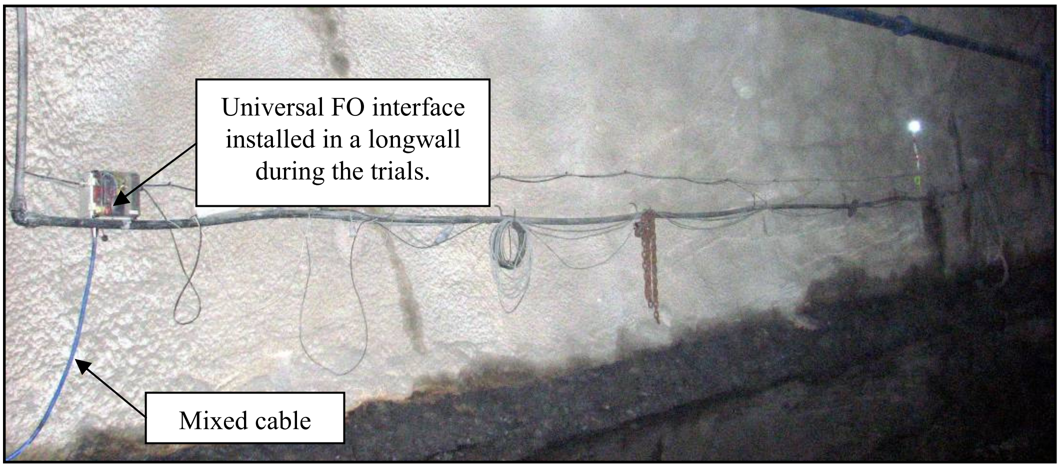



***Figure 3.3.5-3: FO interface installed in a longwall during the course of the trials***

***Transmission schemes for wireless, wired and optical interfaces of databus system.***

In the first quarter of 2009 a series of tests were carried out by EMAG in underground workings of Guido mine Zabrze in order to verify proper operation of transmission schemes for wireless, wired and optical interfaces of databus system. First tests were carried out with the early prototypes of wireless diagnostic sensors for vibration and temperature monitoring developed in WP3 (***figure 3.3.5-4***). During these tests correct operation of wireless transmission protocol was verified. By the way sample data regarding 3-axial vibration levels in free run mode of the shearer were collected. Analysis of the system behaviour helped to improve the data collection and buffering schemes. The modifications were introduced later on to the embedded sensor firmware making possible spectral analysis of vibrations with resolution of 512 FFT points per axle.

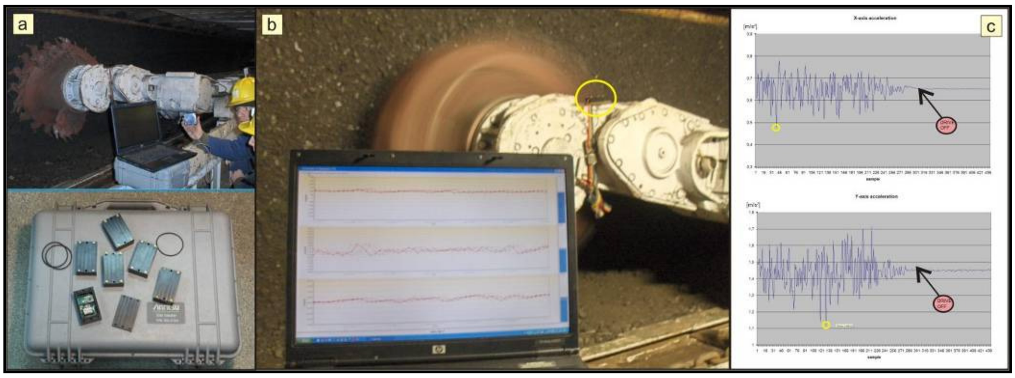



***Figure 3.3.5-4: First trials of transmission schemes in Guido mine***

To facilitate tests of the WDM interfaces type µZIST developed by EMAG in WP4 a fibre optical connection was established through the shaft to level -320m of Guido mine. The µZIST stations were connected in simple network consisting of one surface station and two underground stations. To enable trials with the communication backbone the surface station was located in the mine control room (see ***figure 3.3.5-7, page 83, top left***) whereas the underground stations were installed in temporary locations at level 320 (see ***figure 3.3.5.5c, next page*** left/right upper part). The tests were carried out with the improved revision of diagnostic sensors with spectral analysis capabilities (see ***figure 3.3.5-5 a, b***). During the tests both local and remote data acquisition and visualisation mechanisms were proved to operate correctly. The high speed data link capabilities of the developed databus system were also tested with use of digital video streams from two Ex cameras type OKO-1 which were connected to the µZIST stations. The databus system enabled online video monitoring from the surface (***figure 3.3.5-6***, next page).


*Figure 3.3.5-5: Second stage of trials including the FO- interfaces and wireless gateway*


*Figure 3.3.5-6: Tests of high speed databus capabilities – online video monitoring (screenshots)*

### 3.3.5.2 Testing the visualization and monitoring system in a selected mine

***SCADA System***

The tests of the SCADA visualization system, which were performed in IFIX software within WP3 The computer software used for diagnostics was made independent from main SCADA visualization, were carried out within task 5.2 (chapter 3.3.5.2) based on real data of machines operating in mines and stored on memory cards. Moreover, tests of ITGKomMoxaMenager software were carried out.

The data from mining machines were transferred to the relation data base with software developed within WP3, in which it is described in detail. The tests of the system included:

- Comparison of data taken from recording cards with data generated by simulation software developed for PLC controllers manufactured by Beckkhof Company. The comparison consisted in checking the ranges of variability of physical amounts and simulating amounts and their correlation with values given in technical documentation of machine.
- Entering of data from recording cards for visualization of SCADA system.
- Verification of correctness of displaying of visualization components for real data.
- Verification of correctness of operation of NEMAEQ SDA software and its comparison with information from technical documentation of machine.

***ITGKomMoxaMenager software developed as KOMAG's contribution to Task 4.4 WP 4 (chapter 3.3.4.4).***

The tests were conducted on a device operating Simple Network Management Protocol (SNMP), on which the software operation is based on. Broader information about the software are in WP4. The device operates as a part of KOMAG's network infrastructure and it is continuously loaded. It enabled to test the software in real conditions. All functions made available by the software, including first of all continuous monitoring of selected parameters as well as recording and reading of single configuration settings of device, were tested.

***Transmission Schemes for Wireless, Wired and Optical Interfaces of Databus System.***

After first positive test results were obtained with particular components of the databus system the whole system was integrated with the software enabling local (underground) and remote (surface) visualisation and monitoring. The test installation intended to verify its operation was deployed by EMAG in Guido mine. The connection diagram and location of particular components are shown in ***figure 3.3.5-7.***

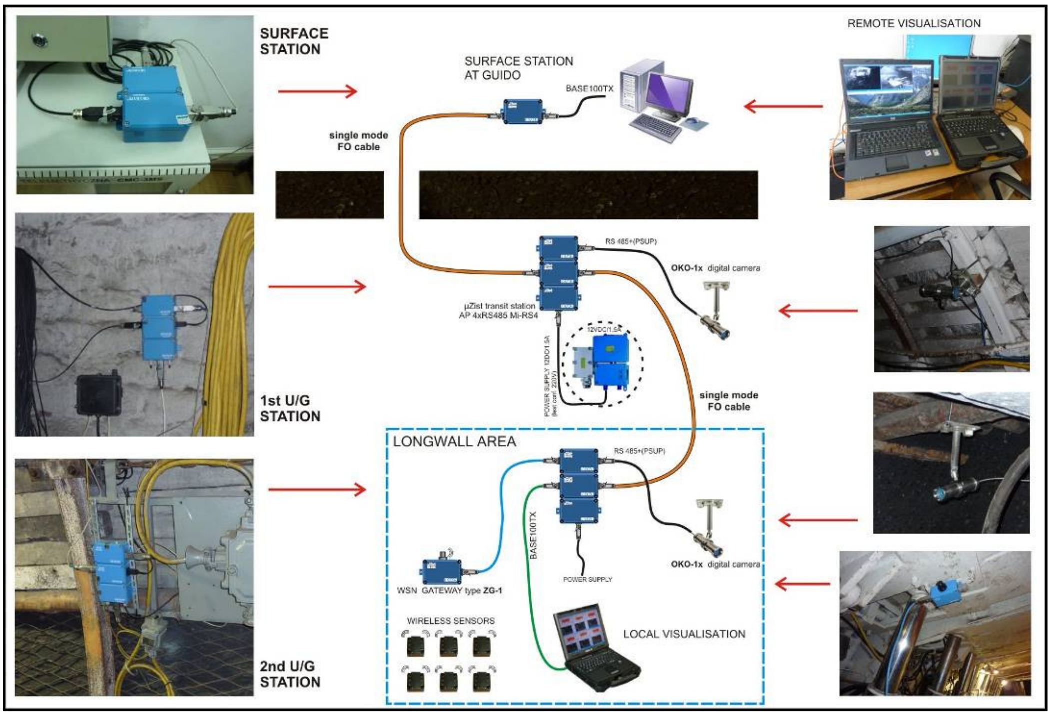



***Figure 3.3.5-7: Final test installation deployed in Guido mine for transmission schemes***

The underground µZIST stations were moved to their destination locations (in the transformer chamber and the longwall exposition). The two underground stations were interconnected by means of single mode WDM optical connection while the first station was connected with the surface station by FO cable installed in the shaft.

A digital video camera type OKO-1 was installed in the roadheader exposition chamber and was connected to the first µZIST station. The interfaces of the second µZIST station enabled the connection of another camera (installed in the longwall exposition), a wireless sensor gateway (via fieldbus interfaces) and local visualisation equipment (via Ethernet connection).

In course of the test series a batch of final revision 3-axial vibration and temperature sensors with (improved firmware revision and mechanical design) were tested on the shearer and the AFC (see ***figure 3.3.5-8***). The measurements were collected with wireless gateway (***figure 3.3.5-8c /figure 3.3.5-9c****, next page*) connected to the second µZIST station (see ***figure 3.3.5-9 a***) and enabling local as well as remote data collection and visualisation.


***Figure 3.3.5-8: Testing operation of wireless sensors in Guido mine***

For the local visualisation a laptop PC running the developed dedicated spectral analysis software was connected to Ethernet interface of the second µZIST station (see fig. 4.3.5.9b). In such configuration the software was able to simultaneously visualise the waveforms and spectral component plots of two 3-axial sensors per one screen and log data of all 16 = (4x3) vibration + 4 temperature channels.

***Figure 3.3.5-9: Test installation in the longwall exposition of Guido mine***

The test installation also enabled to run the visualisation and monitoring software in surface control room of Guido mine and remotely connect to wireless sensor network, manage the databus interfaces or run the digital video surveillance software. For that purpose the surface µZIST station was connected to the local Ethernet network of the mine using the provided Ethernet interface. Thanks to such connection it was possible to run the visualisation and monitoring software on two independent laptop PCs connected to the network and interact with underground devices.

The communication system enabled a smooth operation of the visualisation software for wireless sensors and simultaneous video streaming from two digital video cameras (***figure 3.3.5.10***). At the same time each of underground stations could be remotely reconfigured if necessary.

***Figure 3.3.5-10: Remote monitoring from mine control room of Guido***

The test results were satisfactory as during the numerous trials the transmission interfaces didn't introduce any noticeable delays which made possible online operation and interaction with underground equipment. It is worth noticing that the communication backbone of the test installation has been flawlessly operating in Guido since Q1 2009 which to large extend proves reliability of the developed WDM devices and promises good prospects for commercialisation.

***Feasibility of ATEX Water-in-oil Transducer***

Comparative tests on six commercial water-in-oil sensors under Task 3.2 (chapter 3.3.3.2) led to the conclusion that the Vaisala MMT318 outperforms all the other sensors. On the basis of this conclusion the adaptation of a Vaisala sensor system for use in the mining industry was investigate. Meetings were held with Eickhoff G.B. and Vaisala to examine engineering specifics. Various representative shearer models were examined in terms of accessing transfer gearboxes for sighting of transducers-electronics, and in terms of the available analogue interfaces and power supplies

In terms of the feasibility of adapting an existing water-in-oil transducer for ATEX M1 or M2 approval, detail engineering discussions were held with Vaisala under the provisions of a non-disclosure agreement. A number of material selection and design issues were identified that would need to be addressed.

These included the following points:

1. The transmitter and display unit, with overall dimensions 164 x 115 x 73mm was considered too large to be readily accommodated onboard any current shearer design.
2. The casing material employed Group II/III alloy materials which would require substitution in a mining ATEX version.
3. The power supply and analogue interface connections were limited to 4-20mA, 0-24V.
4. The CENELEC EEx ia IIC T4 classification was not directly suited to mining but suggested adaptation and recertification would be feasible.

Discussions with Vaisala indicated that it is technically feasible to adapt their existing products to produce an ATEX M1 or M2 certificated water-in-oil transducer. However, from a commercial perspective, the manufactures response to these discussions is likely to hinge on the redesign/adaption and certification costs compared to the predicted CENELEC ATEX mining intrinsically safe market size. Furthermore, the retro-engineering considerations to install the sensor heads were onerous. In particular, the fitment of transducers and power/data connections to any transducers located in ranging arm transfer gearboxes would entail significant engineering design changes.

Consequently, an alternative sensor with a monitoring and transmission technology that would facilitate a more immediate implementation strategy was examined. This work was undertaken in close collaborating with EMAG who have produced a prototype "water presence/level" sensor as part the of the wireless, explosion-proof machine monitoring sensor network being developed under Task 3.2 (chapter 3.3.3.2).

Following adaption of the interface to the prototype sensor to facilitate laboratory trials, comparative tests against the commercial sensors that have already been evaluated by the project were undertaken. The tests were carried out to compare performance of the prototype using the Vaisala MMT-318 as a reference sensor. The measurements were carried out with 'Powerdraulic' oil and 'Powergear' oil types. The achieved results (see ***figure 3.3.5.11***) are very promising and demonstrate that the EMAG prototype tracked the reference Vaisala sensor well.

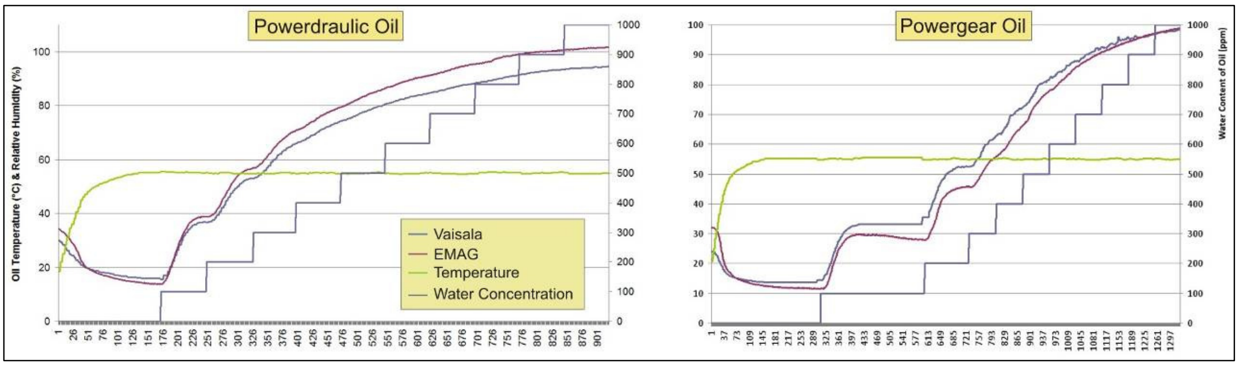



***Figure 3.3.5-11: Test results of prototype water in oil sensor***

The correlation coefficient is very similar for both oil types which suggests that calibration against particular oil types may not be necessary. Additionally it could be observed the prototype unit also displayed a well damped output, free of some of the short-term fluctuations manifest in other water activity sensors.

### 3.3.5.3 Testing of assessment tools and identification of approaches to improve human reliability

The maintainability assessment software developed under Task 3.4 (chapter 3.3.3.4) was used to conduct a range of field testing and evaluation exercises. These evaluation exercises were undertaken with the assistance of mining maintenance managers, supervisors and artisans.

The primary objective of the maintainability assessment tool is to produce metrics, maintainability "scores", to facilitate cross machine comparisons and aid in equipment selection and/or provide a means to assess the potential value/impact of retro-fit modifications. Whilst the initial evaluation exercises were not designed to test all aspects of the tools they did serve to provide a valuable indication of software “usability” and allow the potential for the tools to be used to assess the physical effort required from maintenance staff and then combined with a measure of their perceived “importance” of doing the task correctly to provide an indication of potential human reliability issues.

The testing and evaluation protocol adopted during these initial trials was:
1. Users given an introductory briefing and demonstration in the use of the maintainability assessment tools
2. Each user asked to use the maintainability assessment software to assess a maintenance task with which they were routinely involved
3. Subjects complete a violation potential questionnaire, targeted at the maintenance task assessed in step 2.
4. Conduct structured interview with each subject and obtain estimates of risk of using the risk perception measurement tool.

The results derived from these users trials have been used to guide and structure the development and refinement of the maintainability and human reliability assessment tools being undertaken in Task 3.4 (chapter 3.3.3.4). The principal results and conclusions derived from the testing and evaluation exercises included:
- User feedback indicated that the display and user interface aspects of the software was straightforward and relatively simple to use (all subjects had previous experience of working with MS windows software).
- Initially, users frequently encountered difficulties in terms of identifying the correct/best “nodes” to use to represent the task elements they were attempting to describe. These problems were addressed by improving the node selection interface and by implementing context specific help facilities to supplement and ultimately replace the original user manuals.
- Analysis of the responses to the violation questionnaire combined with later debriefing discussions with the subjects indicated that their reposes tended to influenced by the generic problems they encountered whilst undertaking maintenance tasks rather than problems that were directly related to the specific task being examined. Consequently, an “electronic” version of the questionnaire, with dynamic task descriptors in the question set, was produced.

The results obtained from the violation questionnaire indicate that the influential factors being identified as contributing to violation potential tend to be related to organisational issues more often than equipment design limitations. Hence, the questionnaire will compliment the results gathered by the maintainability index rather than duplicate them.

Results from the risk perception questionnaire proved to be very valuable in terms of facilitating structured interviews. However, discussion with mine staff indicated that whilst these results were valuable to human factors specialists, their direct value to other mining professionals may be limited. Consequently, alternative methods of providing “risk” indicators that are of more direct utility to the mine staff were investigated.

Risks arising from poor maintenance can result in various combinations of:
- Equipment damage costs – repair time & replacement parts
- Production losses
- Health and Safety hazards

A number of alternative user interface modules were produced under T3.4 to allow user estimates of the above range of risks to be elicited and their responses to be included directly into the maintainability assessment tree structure. Subsequently, user feedback, obtained during field trials of the maintainability assessment software, was used to identify the preferred interface design options and these have been now been employed in the final risk estimation module (see ***figure 3.3.3-13, page 62***).

#### 3.3.5.4 Linking of monitoring and control technology for the fully automated control of shearer loader operations and underground field test

Besides various underground tests of single sensors and subsystems one field test took place during the project lifetime between January and October 2008 at Prosper Colliery comprising the whole automation system *(**figure 3.3.5-12**, next page).* The purpose was to check the overall functional capability and to record measuring data to enable offline simulation for software improvements and determination of parameters. The findings also enabled a series of major improvements and adjustments which could be realized in the workshop phase between January and April 2009 as an

precondition for the implementation of the project result. After the project end, the revised shearer was subjected to a final test in October 2009 at Auguste Victoria Colliery in which the applicability of the the whole system could be demonstrated convincingly.

***Figure 3.3.5-12: Automated shearer loader in workshop and during field test***

The following concentrates at the sensors as core elements of the automation system. The other "enabling" systems were inherent part of the tests – otherwise the overall functionality wouldn't have performed at all. Hence this aspect is not reported explicitly in the following.

The IR sensors itself were successfully tested for their overall functionality. The system proved its general efficiency and robustness. The measuring series resulted, for the first time, in a complete longwall image along the entire coalface of 360 m in length. Extremely irregular and unstructured geological textures of the seam in which the system was tested and a poor contrast between coal and rock led to distinct contrast fluctuations which could be rectified neither through adaptation of the threshold values nor through adaptation of the sensitivity of the algorithm. Differentiation was barely possible with the human eye ***(figure 3.3.5-13).***

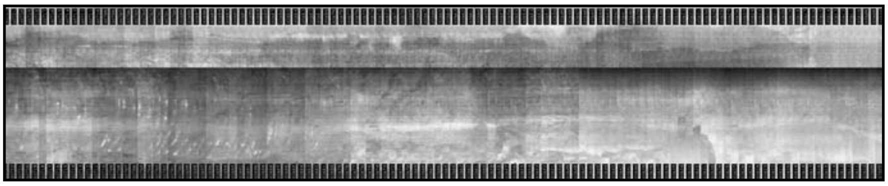
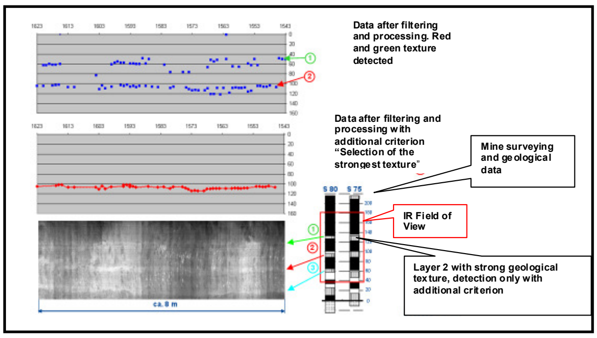


***Figure 3.3.5-13: Unstructured geological textures in the seam***

This initiated the development of further filters criterions in order to ensure detection even under poor geological conditions. ***Figure 3.3.5-14*** shows the improvement obtained in a simulation.[9]



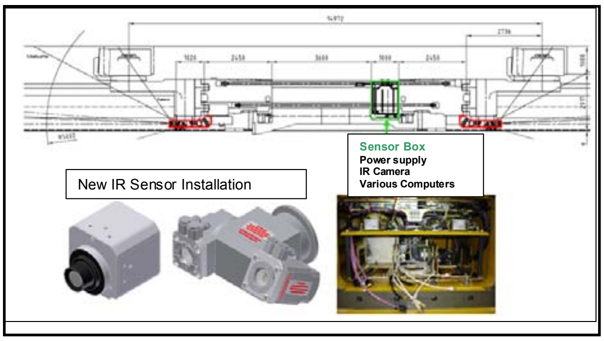




***Figure 3.3.5-14: Simulation of the coal interface following: two detected layers (blue dots); below identification and display of the layer with the strong texture by the new filter and Sensor Box & IR Sensor System (right)***

[9] As the shearer was dismounted already when the additional filter criteria were developed and implemented , the functionality of the improved interface detection could only be verified in laboratory**.** It could however be implemented successfully in the second underground application in 2009 reported below.

The positioning of the IR sensor box had to be revised several times according to experience gained during the tests. ***Figure 3.3.5-14*** shows the optimized final position (green marking) and the fitted module of the recent IR-Sensor.

Three measuring series were recorded with the radar- sensor**.** During the measuring series, all dynamic measurements were mapped into a static measuring grid as a function of the recording location. Although the dust layer at the Ge window was intentionally removed only in the course of the attenuation measurements, no functional impairment was found even with the dirty window. The attenuation difference determined during the tests was negligible. A minor raw data quality of the left sensor resulted from the adverse direction of mine air and conveyor load. As a consequence it was decided to integrate the camera in the front of the monitor box instead of the edge thus preventing an occlusion of the radar device for the next application.

All in all the underground implementation of the radar was successful. The radar detected objects in the defined collision area early and precise enough to adjust the ranging arm position without interrupting the production. It also identified the conveyor load in time for a proactive coal flow management.

Field testing of the Machine Gateway, the Machine Server devices and respective software was performed not only in combination with the mentioned devices but also elsewhere. The improvements of the Gateway on a fully WLAN connected shearer loader was successfully tested at the manufacturer ZZM in Poland and later on a commercialized basis through an external Polish company showing the impact and commercial importance of this project achievement. In an existing installation at Premogovnik Velenje in Slowenia the improvements of the project were tested and successfully implemented on a commercial basis through the machine manufacturer.

The multiple redundancy of the Machine Gateway was successfully tested underground at DSK. In a later phase, these were already commercialized in an application in Australia. The device was also tested outside the project on different types of machines like on a borehole drill rig. Also this test could be commercialized directly with the German machine manufacturer DHMS in an application at DSK.

The Machine Server has also been successfully tested in the related underground applications also directly migrating into commercial use not only on shearers but e.g. also in an application on monorails with DSK.

## 3.4 CONCLUSIONS

Conclusions, achievements made

### 3.4.1 Automation of longwall equipment (WP1)

The objective of a full automation of the shearer operations has been obtained to the greatest extent; the technical prerequisites for automatic face navigation could be met. This is underlined by the fact that many technologies developed in the project have been adapted meanwhile by other mines.

Coal/rock interface detection is achieved through two infrared sensors covering the whole seam height whereas the layer between the seam and the floor can be detected by impact sound sensors as long as the difference in cutting resistance between coal and rock is sufficient. Algorithms and a robust image processing process for picture editing and data interpretation provide reliable boundary detection with a precision of +/- 50mm; the system fulfils the requirements imposed on automation. An additional tool was developed assisting the operator to take over and to perform coal interface detection even under extremely poor geological conditions, i.e. areas with irregular and unstructured geological textures.

Collision avoidance at face ends and positioning in the longwall is achieved through a system of synchronization switches at the shearer and magnets at the conveyor. The shearer position can be ascertained at face ends with a precision of +/-1cm through compensating software. The accuracy of wireless sensor technology turned out to be too low for the purpose, this technology can however be exploited in other applications with lower accuracy needs.

For obstacle detection in the longwall a 77GHz dual- range radar sensor proved best. Thanks to sophisticated evaluation software the radar detects objects early and precise enough to adjust the ranging arm position without interrupting the production. It also identifies the conveyor load in time for a proactive coal flow management. An additional video camera with LED headlights improves the safety in the longwall and the overview in the surface control centre over the face situation when the shearer is operated automatically. The compensation of the distorting effect of changing radar vision range and its permanently changing height could not be obtained satisfactorily. A more precise method using inertial navigation could not be tested any more during the project.

All sensors and attendant components are integrated in such a way that protection and functioning in the harsh longwall environment is provided.

Conveyor overload and undesired downtime is avoided successfully through a load-dependent regulation of the shearer loader speed. Software for controlling and communication between conveyor and shearer loader reduces the shearers tramming speed automatically according to the conveyor load if necessary. If a defined overload limit is exceeded, the shearer is stopped.

For the integration of the complex sensing technologies the IT level computing infrastructure has been upgraded through a network of several computers and web technologies on the machine. Special networking capabilities providing multi redundant links ensure a reliable uninterrupted communication between the shearer and the mine's central IT infrastructure. An embedded machine server acts as a web server for machine information. For network security reasons the machine network functions are separated from the IT level machine control through a network gateway on the shearer enabling the machine server to concentrate on application functions while the separate gateway assures the secure external mine network communication.

Due to different technologies and geology face end technologies used elsewhere in the world are not applicable for automation in German collieries. As partial solution to improve the situation at face ends concepts for easy to handle lining, novel props and a novel face end shield are proposed.

### 3.4.2 Optimisation of the cutting and loading process for Coal Shearers, Continuous Miners and Axial and Transverse Roadheaders (WP2)

A literature review confirmed FLAC3D to be the best numerical modelling package available at the time of project commencement to simulate rock failure in the manner required. The subsequent modelling demonstrated that FLAC3D can successfully be used to predict the cutting force when a mechanical pick initiates breakage in rock. The chipping failure mechanism indicated by FLAC3D is one of shear to adjacent free surfaces and the relevant rock parameters, based on the Mohr Coulomb failure criterion, are the cohesion and angle of friction. Using this mechanism and by varying these parameters the essential features of experimental rock cutting studies can be reproduced including the chipping force magnitude, variation of cutting force with pick wedge angle, pick width, depth of cut and cut spacing.

Deliverable 2.1 gives the methodology for analysis of the rock failure mechanism under machine tools and indicates that the numerical modelling has the potential to replace the expensive cuttability test, (where triaxial rock properties are known), and to quantify pick forces and specific energy for realistic cutting geometries thus making a significant advance compared with conventional laboratory testing.

Another literature review on drum design identified advances in drum technology since the 1980's, including the wider introduction of continuous miners and transverse roadheaders and increased machine power.

The database of actual drum designs (lacings), also used to identify advances in drum technology, was totally dependent upon the response of companies and mines from whom they were requested which was beyond the control of RMT. The resulting database was smaller than expected but sufficient data was acquired during the early stages of the project for software specification and development. An initial working version of the software was developed which allowed 3D visualisation of a cutting drum, breakout patterns analysis and display of the calculated force balances on the drum. This was for continuous miners and transverse roadheaders as well as axial roadheaders and shearers. This work facilitated the.Analysis of Current Drum Designs by the New Software and Software Revision.

The initial working version of the software did not incorporate the capability of analysing the sumping action of an axial roadheader and the slewing action of a transverse roadheader. These were included under the software revision along with writing the software in a more future proof programming language, Microsoft's .Net2.0. The drum design software was successfully developed.

As part of the drum design analysis, practical design tools and field applications were investigated and trialled. This has led to a suitable methodology for drum design optimisation incorporating: 'Stage 1' Site and Drum Analysis studies to determine the factors contributing to poor cutting performance (pick consumption surveys, rock property tests on the coal and any stone bands cut, rock property data from numerical modelling, metallurgical tests of the picks, thermal imaging of the drum and CAD analysis of the drum design using the new software). 'Stage 2' Drum re-design/optimisation using CAD analysis based on the 'Stage 1' information and finally 'Stage 3' Further pick consumption and thermal imaging surveys to confirm improved performance and identify any other potentially beneficial changes. Field trails including the trial described in this report illustrated that pick consumption rate can be considerably improved by application of this methodology.

Golder RMT, has a network of connections within the industry and clients have been alerted to the improved capability. Advice is currently being given to a European client on the cuttability of roof and floor rock for an new mining prospect and later work may include specific designs for rock cutting. An abstract has been written for submission to a Conference in order to disseminate the results to a worldwide audience.

## 3.4.3 New methods for monitoring/diagnostic of machine operations/conditions, maintenance and maintainability (WP3)

The visualisation system developed facilitates the monitoring and control of all the devices typically found on a mechanised longwall face. This includes the shearer, AFC and powered roof supports. The diagnostics system (NEMEAQ FDA) is able to cooperate with any other data processing and monitoring system used on a longwall system and hence provides a platform that can take advantage of the improved thermal imaging camera, wireless sensors and a water in oil transducer developed as diagnostic devices. In the future it will be possible to expand the visualization system to form a system capable of processing, monitoring and analysing the data collected from multiple longwall faces.

An improved thermal imaging camera, wireless sensors and a water in oil transducer were developed as diagnostic devices employing extensively novel technologies such as ultra low power analogue electronics, state of the art wireless technologies, MEMS devices and uncooled microbolometric infra red arrays. Thanks to that it is possible to achieve operation within the energy and surface temperature safety limits required for explosion-proof design. The achieved performance is on par with that of commercially available devices whilst their design enables their application in the mining industry.

A solution for a wireless monitoring network was developed to be compatible with the fibre optical transmission system developed in WP4. The field trials in WP5 proved its good integration with the remaining part of the complete sensor to visualisation software path.

The existing maintainability issues and limitations could be identified and delineated thus establishing the baseline information and data required to develop the maintainability assessment tools. The results and conclusions derived are reported within D3.4 - "Limitations in the Maintainability of Mining Machines. The maintainability assessment tools developed were shown to provide facilities which will allow the industry to:

- Compare maintainability across machines with similar functions, and hence aid equipment selection,
- Assess the impact of potential design improvements/retro-fit modifications to improve maintainability and hence improve production performance and reliability,
- Assess the physical effort required from maintenance staff. This assessment, combined with a measure of the artisans' perceived "importance" of doing the task correctly can be employed to provide an indication of human reliability.

The maintainability assessment criteria embedded within the assessment software has also been used to produce a series of generic recommendations to the industry. These are contained in D 5.2 - Final report and recommendations to industry.

## 3.4.4 Data transmission by FO based Fieldbus-Systems (WP4)

According to a comprehensive analysis 50/125 glass optical fiber is seen most appropriate for implementing a tactical F.O. link. due to its overall balance of features and performance. Functional prototypes of expanded beam fiber optic contacts, appropriate for use in harsh environment, together with a mixed electro-optical connector were developed successfully. The development of a robust and low cost fiber optic contact, with the possibility of being field-assembled, opens the doors to the design of a new generation of equipment for control and monitoring, with improved functionality thanks to the use of a high bandwidth communication network.

An intrinsically safe prototype of modular and universal fiber optic interface for tactical applications was implemented. The adaptation of commercial devices for underground use (ATEX certificable) was done and the ATEX certification process has been started. Interface devices employing innovative Wavelength Division Multiplex technology were developed. They make possible large savings with regard to fibre-optical cable usage, long distance communication and versatile interconnection with basic industry standard interfaces. Prototype devices were tested and their performance was positively verified in the laboratory and underground installation in Guido mine. Possible applications include but are not limited to mine-wide automation and control backbone networks and systems interconnection.

A complete software tool to configure and manage the network parameters has been developed. This software allows to the user to perform the continuous changes that a tactical network needs, using a graphical interface and accessing to all the devices connected to the network in the same application environment.

### 3.4.5 Underground testing (WP5)

***Databus System***
In field tests the tactical communication system based on FO has demonstrated to provide new features in the mine control and monitoring systems field as well as solve some of the existing problems. An example of a typical application improved by the installation of this kind of systems, and demonstrated during the trials, is the common background noise existing in the speech communication systems based on analogue transmission.

The developed digital communication system is capable to transmit voice in a digital way and stands the harsh mine conditions. Thus the problems of signal loss in long fieldbus based on copper wires causing illegible signals for the receiver can be overcome. Fundación "Santa Barbara" is allready using this technology to perform voice communication in its installations and the Spanish mining company HUNOSA has ordered the first batch of digital roadway amplifiers for its mines.

During numerous trials the transmission interfaces didn't introduce any noticeable delays which made possible online operation and interaction with underground equipment. The communication backbone of the test installation has been flawlessly operating in Guido Mine since Q1 2009 which to large extend proves reliability of the developed WDM devices and promises good prospects for commercialisation.

***Visualization and Monitoring System***
In field tests the correctness of operation of SCADA software included in visualization system could be verified.

Errors in software operation and discrepancies detected during tests of the advisory and diagnostic software have been analysed. On this basis corrections are done currently in order to provide a revised version. At the same time KOMAG tries to interest potential customers with the software. Additional information obtained from customers will enable further improvements.

The visualization of longwall system operation, which was made in iFix software is ready for implementation and available. An important advantage is its easy adaptability to customer requirements, through script generation.

***Water in Oil Sensor***
A commercially available water in oil sensor with performance characteristics that match the measurement requirements of the industry has been identified. Technical challenges, primarily in terms of gaining ATEX certification, indicate that, at best, the availability of this device in a form that could be used by the industry would involve long lead times. Furthermore, in the light of a shrinking mining equipment marketplace the manufacturer's commercial considerations are likely to result in this solution not being realised.

However, the prototype water-in-oil sensor subsequently developed and tested by the project had been shown to performance equally as well as the commercial offering. Furthermore, the prototype sensor is far more amenable to ATEX certification and the final development and implementation of a practical device is achievable in significantly shorter time scale.

***Assessment Tools and Identification of Approaches to Improve Human Reliability***
The on-going programme of field testing, end user trials and evaluations of the maintainability assessment software toolkit has ensured that the primary assessment tools can be used independently by mine based maintenance staff. Moreover, this process has also served to guide the selection and development of assessment techniques and hence, optimize the practicality and relevance of the assessment tools to the needs of the industry.

Mine trials have also demonstrated that the primary assessment tools can be used by mine maintenance staff to conducts cross machine comparisons that will aid in equipment selection and/or provide a means to assess the potential value/impact of retro-fit modifications.

***Linking of Monitoring and Control Technology for the Fully Automated Control of Shearer Loader Operations and Underground Field Test***

A field test comprising the whole automation system revealed its overall functional capability. The findings also enabled improvements and adjustments to be realized in the subsequent workshop phase.

The IR sensor system proved its general efficiency and robustness. Extremely irregular and unstructured geological textures of the seam in which the system was tested initiated the development of further filters criterions in order to ensure detection even under poor geological conditions. The positioning of the IR sensor box could be optimized during the underground test.

The underground implementation of the radar was successful, too. The radar detected objects early and precise enough to adjust the ranging arm position in time. It also identified the conveyor load in time for a proactive coal flow management. Dust at the Ge window unavoidable in alongwall environment caused no functional impairment. The attenuation difference determined was negligible.

“Enabling” installations as the Machine Gateway, the Machine Server and the respective software were inherent part of the tests. Most of these devices were tested successfully also in other applications, e.g at the shearer manufacturer ZZM in Poland and at Premogovnik Velenje Mine in Slowenia showing the impact and commercial importance of this project. Meanwhile the Machine Gateway is being applied in an Australian mine and tested on different types of machines like a borehole drill rig. The Machine Server is being applied also in a monorail application on with DSK.

After the project end, the revised shearer was subjected to a final test in October 2009 at Auguste Victoria Colliery in which the applicability of the whole system could be demonstrated convincingly.

## 3.5 Exploitation and Impact of the Research Results

This section addresses issues related to the exploitation and impact of the research results. It comprises information on:

- actual applications;
- technical and economic potential for the use of the results;
- any possible patent filing;
- publications and conference presentations resulting from the project;
- any other aspects concerning the dissemination of results.

### 3.5.1 Automation of longwall equipment (WP1)

#### 3.5.1.1 Determination or establishment of the parameters to be observed and the state of the art and knowledge from previous projects

This work facilitated the developments in Task 1.2 (chapter 3.5.1.2).

#### 3.5.1.2 Recognition of coal/surrounding rock interface, collision avoidance, load-dependent speed regulation and shearer loader location

The research and the positive test results achieved open up the broad application of the automated shearer loader. Except the automation of the face ends all requisites are accomplished. The economic impact fulfils the expectations expressed in the proposal: Compared with the average of all 8 shearers used at DSK (including the automated one) the productivity could be enhanced through the automated shearer from 59,5 tons coal per man shift to 110,6 t/MS. The area rate of advance, a key figure for efficiency, could be improved from 3,94 $m^2$/min (DSK average for shearers) to 6,28 $m^2$/min. Additionally the effort for maintenance and the repairs could be reduced significantly compared with the standard shearer.

The shearer loader automation with the developed automation features saves one miner per shearer and shift, i.e 3.MS per day and face. It leads to less abrasion of cutting tools and reduces the amount of rock to be cut and to be transported and separated in the preparation plant. That is why DSK has bought meanwhile a second automated shearer which will go productive from May 2010 on at Auguste Viktoria colliery.

Moreover DSK has decided to buy and apply only automated shearers in future. Another prove for the appraisal of this project is that NEMAEQ obtained the annual DSK innovation award in 2009. The development was already introduced to the public at the APCOM conference, Santiago, Chile, April 2007, Sweden, June 2008, the RWTH Aachen International Mining Symposium 2009 and the MassMin Conference, Luleå. In the Aachen Colloquium the manufacturer also reported that the know how gained with NEMAEQ forms a valuable basis for the automation of a bigger shearer for an Australian colliery and even for Chinese mines. 2009 the project was published in the German standard Mining Magazin "Glückauf", and in "International Mining". In the meantime the automated shearer is proposed as candidate for the Innovation Award 2010 of the BAUMA, the International Fair for Mining and Construction Machines where the automated shearer loader will also be displaced.

However, the project results are not only applied for shearers. Most of the components and solutions developed are also deployed for the following other applications:

- The infrared technology can also be applied for discharge monitoring of conveyors in order to avoid blockages particularly in rough environments as in underground and surface mining operations and in construction industries as well.
- The development of the load dependant shearer speed regulation was extraordinary successful. This overload protection system was and is being invented in many German and European collieries.

- The Wireless sensor technology could be exploited in two other RFCS projects and enabled the successful implementation of a 2D tracking system for vehicles and personnel with lower accuracy needs.
- The Machine Gateway system is used also in other in shearers by the German manufacturer Eickhoff. The units are installed in a number of machines in Slowenia (Premogovnik Velenje) and in Australia. Also Polish shearer manufacturers are evaluating commercial use. The Machine Gateway furthermore is commercially used on different other machines in underground coal mining such as drill rigs by the manufacturer Deilmann Haniel Mining Systems.
- The seamless WLAN roaming developed for a reliable shearer communication is used today as a de facto “state-of-the-art” in WLAN communication for mine machinery as shearers, monorails, drill rigs and autonomous loaders in hard rock mining together with the machine manufacturer Atlas Copco Rock Drills AB (Sweden).
- After generalization of the ATEX certification the 24 GHz radar sensor, dropped for shearer automation, is commercially available for obstacle detection and profile clearance detection of free moving machinery in underground environments.
- The MachineServer is used for a network based systems integration of high level intelligent sensors such as laser scanners or radar scanners and multimedia components such as digital video. In monorails at DSK, the device is used for network based data acquisition and on board preprocessing as well as for WLAN based machine tracking and data communication. The base technology is also used in a commercialized unit marketed to a machine manufacturer in metal mining.

#### 3.5.1.3 Alternative face end support systems and automatic pushing devices

The original objectives could not be obtained due to lack of applicability and comparability of solutions found elsewhere in the world. Hence Deliverable D1.3 could not be produced in the originally planned form. It now covers “Face End and Automation Technologies”. Alternatively concepts for easy to handle lining, novel props and a novel face end shield were developed but could not be exploited directly; they may however form a basis for further considerations as face end automation remains a challenge.

#### 3.5.1.4 Deliverables of WP 1

| Code. | Deliverable | Type |
|---|---|---|
| D 1.1 | Suitable sensor technology for recognition of coal/surrounding rock | Prototypes |
| D 1.2 | Software for steering and controlling of the shearer loader | Software |
| D 1.3 | Design of alternative face end support systems and automatic pushing devices for the face conveyor drives | Report |

## 3.5.2 Optimisation of the cutting and loading process for Coal Shearers, Continuous Miners and Axial and Transverse Roadheaders (WP2)

### 3.5.2.1 Modelling methodology for optimisation of the cutting process

The modelling has demonstrated that FLAC3D can be successfully used to predict the cutting force when a mechanical pick initiates breakage in rock. This can save time and money with respect to laboratory testing of site specific rocks. This is especially advantageous given that the availability of cuttability tests is reducing. Since the completion of this project the tests are now no longer offered in the UK. The nearest test centre to the UK is now in Turkey.

### 3.5.2.2 Alternative Software Development for Drum Design

This work facilitated the developments in Task 2.3 (chapter 3.5.2.3).

### 3.5.2.3 Analysis of Current Drum Designs by the New Software and Software Revision

The drum design analysis software was suitably revised. As part of the drum design analysis, practical design tools and field applications were investigated and trialled. This has led to a suitable methodology for drum design optimisation incorporating: 'Stage 1' Site and Drum Analysis studies to determine the factors contributing to poor cutting performance (pick consumption surveys, rock property tests on the coal and any stone bands cut, rock property data from numerical modelling, metallurgical tests of the picks, thermal imaging of the drum and CAD analysis of the drum design using the new software). 'Stage 2' Drum re-design/optimisation using CAD analysis based on the 'Stage 1' information and finally 'Stage 3' Further pick consumption and thermal imaging surveys to confirm improved performance and identify any other potentially beneficial changes. This methodology was used on site specific case studies for underground coal mines and demonstrated that significant improvements in cutting performance can be achieved in terms on tonnes of coal cut by each pick.

The software and numerical modelling successfully developed have been applied to coal cutting in underground mines within this project. However is has the flexibility to be used for other applications as it can accommodate a range of drum geometries and rock properties. These applications include other coal mining such as surface and highwall mining. Non coal applications will be where cutting drums are used for hard rock mining and civil engineering tunnelling. It may also be applied to the cutting drums used for road planing and deep piling in civil engineering.

### 3.5.2.4 Dissemination of Results

RMT, now Golder RMT, has a network of connections within the industry and clients have been alerted to the improved capability. Currently RMT are advising a European client on the cuttability of roof and floor rock for a new mining prospect, later work may include specific designs for rock cutting. An abstract has been written for submission to a conference in order to disseminate the results to a worldwide audience. This will be either the 11th AusIMMM Underground Operators' Conference, 21-23 March 2011, Canberrra or Aachen, 2011 at the Sustainable Developent Indicators in the Minerals Industry Conference 14-17 June. The paper is therefore planned for publication in 2011.

### 3.5.2.5 Deliverables of WP 2

| Code | Deliverable | Type |
|---|---|---|
| D 2.1 | Methodology to analyse the failure mechanisms of rock under mechanical tools | Methodology (Report) |
| D 2.2 | Best performing cutting machines in coal mines | Database |
| D 2.3 | Software suite for drum design | Software |

## 3.5.3 New methods for monitoring/diagnostic of machine operations/conditions, maintenance and maintainability (WP3)

### 3.5.3.1 Development of monitoring and visualisation of machinery systems operations and machinery contamination control

The monitoring and visualisation systems, developed within this task will serve to increase the availability of machines and equipment on powered longwall system. The continuous monitoring and analysis facilities for key longwall equipment parameters provided by these systems will result in a reduction of equipment damage and operational failures. To promote these improvements within the industry, an action plan has been formulated, and is currently being implemented, to get the manufacturers of mining machines and mine owners to adopt the systems developed by the project. The potential for wider implementation, via the targeted customer base, is significantly enhanced by the flexibility of the software. The software can be implemented as a complete SCADA system or alternatively integrated with existing systems to provide improved monitoring and/or diagnostic capabilities. The conclusion that capacitive methods offer the best solution for a water-in-oil sensor and the fundamental performance requirements established under this task contributed directly to the development of a functional prototype sensor.

### 3.5.3.2 Development of monitoring hardware (thermal imaging camera, wireless sensors, water in oil transducer

Preventive maintenance carried out by means of thermal imaging and preventive diagnostics employing the developed monitoring sensors can give rise to substantial economic benefits. This can be achieved due to a reduction of machine down-time, as the technology enables parts replacement – ‘on time’ once the pre failure symptoms are observed. Substantial elongation of machine life time can also be achieved by employing online monitoring of vital diagnostic parameters with the use of developed devices.

Their usefulness is not limited to monitoring of longwall equipment. In the case of thermal imaging there is a broad scope of mining applications such as fire prevention, rescue action support, process optimisation where use of this technology can substantially improve economic and safety factors. In the case of the water in oil sensor, its good performance shows good prospects for commercial industrial application not limited to the mining industry. The machine monitoring sensors will be integrated with the shearer control and diagnostic system MAKS-DBC.

Certification and commercialisation of the developed diagnostic devices will be carried out by EMAG’s application and production department.

The wireless gateway devices were derived from a version developed within the RAINOW project. The introduced modifications resulted in a design which enables operation in the harsh environment of the longwall area. The wireless temperature sensors developed in the project were used, after certain modifications, within the MINTOS project (for temperature monitoring of a monorail drive). The wireless sensor network technology with location possibilities (researched in T1.2 & partially T3.2) was extensively used for monorail location (MINTOS) and later on for pinpoint pre-incident location of personnel (EMTECH).

A conference presentation covering the potential of thermal imaging, resulting from the experience gained during the thermal measurements taken in Chwalowice coal mine in January 2007, was presented during the SPIE Defence and Security Symposium 2007 Conference XXIX Thermosense, Orlando Florida USA.

### 3.5.3.3 Identification and delineation of existing maintainability issues and limitations

This task succeeded in establishing the baseline information and data required by Task 3.4 (chapter 3.5.3.4) to proceed with the development of the maintainability assessment tools. The results and conclusions derived are reported in detail within D3.4 - “Limitations in the Maintainability of Mining Machines”.

### 3.5.3.4 Development of Maintainability and Human Reliability assessment tools

Having confirmed that mine maintenance staff can successfully use the primary maintainability assessment tool, but that more specialist experience is required to reliably interpret the results derived from the other tools, it is planned to produce and promote two final commercial versions of the software toolkit. The first version, “Maintainability Assessor”, is for general mining industry use and the other “Maintainability Assessor Pro” for specialist uses.

The benefits that can be derived from improved maintainability are often overlooked and the use of machines that are quicker and easier to maintain is a key area in which substantial savings can potentially be achieved. In this regard, the design of equipment is an important factor that contributes directly to high maintenance costs. The “Maintainability Assessor” version of the software will enable industry users to measure the impact of equipment design features on maintainability for themselves and hence guide decisions in respect of retrofit improvements or equipment selection.

Where maintenance is difficult, physically demanding, time consuming or potentially dangerous, short cuts are taken and some tasks can be neglected. Moreover, the losses associated with maintenance related accidents are significant, since estimates indicate that about one third of coal mining accidents are related to maintenance activities. The “Maintainability Assessor Pro” version of the software will enable human factors and health and safety professionals to identify the underlying causes of these problems and formulate solutions that will allow the industry to minimise the costs they represent.

### 3.5.3.5 Deliverables of WP 3

| Code | Deliverable | Type |
|---|---|---|
| D 3.1 | Monitoring, visualization and controlling system | Prototype |
| D 3.2 | Investigation/recommendations on candidate methods of oil contamination monitoring | Report |
| D 3.3 | Monitoring hardware (thermal imaging camera, wireless sensors, water in oil transducer) | Prototypes |
| D 3.4 | Limitation in the maintainability of mining machines | Report |
| D 3.53 | Maintainability and human reliability assessment tools | Software |

### 3.5.4 Data transmission by FO based Fieldbus-Systems (WP4)

The possibility of installing a fiber optic network in a harsh, highly changing mining environment has been welcomed by HUNOSA, a big Spanish mining company. Currently a pilot project for installing a network of fiber optic in one of their coal mines, using results from the whole work package (FO Connectors, Media converter, monitoring software) is being implemented (although these exploitations already have installed a single-mode fiber for networking two shafts, they are interested on implement a complementary tactical network to be extended to exploitation areas and to integrate in it IP video surveillance cameras).

#### 3.5.4.1 Basic Research and Technology Selection

This work facilitated the developments in Task 4.2 (see 3.5.4.2).

#### 3.5.4.2 Connector and Cabling development

A mixed connector and cabling system was developed in collaboration with a Spanish connector manufacturer (ICP). Before this manufacturer stopped business due to the financial crisis, a prototype of mixed connector was shown in MATELEC (*Salón Internacional de Material Eléctrico y Electrónico* – International Fair of Electric and Electronic Material) 2009 year edition, having a positive feedback from the visitors. This new design will be also applied in other related fields with harsh environments, like tunnel construction, in those AITEMIN expects to introduce this new product. Also the Polish project partner EMAG is interested to commercialise the device.

#### 3.5.4.3 Interfaces development

HUNOSA is interested in the implementation of a FO underground network using the FO media converters developed in this task in their mines. It will allow the installation of more powerful process control devices with direct intrinsically safe Ethernet connection, as well as the integration into the FO network of IP video cameras.

In addition, and as result of the RAINOW project, a ZigBee based personnel localization system is going to be implemented in various HUNOSA mines. This system will also use the FO network to send the information of the underground personnel location to the surface. The PAN coordinators will be directly connected with the universal interfaces using an intrinsically safe Ethernet port. In addition, this flexible network infrastructure will be also used in some activities regarding to personnel safety/localization currently performed in EMTECH project.

The interface devices employing WDM technology make possible large economical savings with regard to fibre-optical cable usage. They are characterised also by long distance communication capabilities and interconnection with basic industry standard interfaces. Prototype μZIST devices were tested and their performance was positively verified both in the laboratory and in underground conditions (Guido mine). The devices will be certified and commercialised by application and production department of EMAG.

The prototype μZIST system is used as backbone transmission system interconnecting the location and diagnostic subsystems for monorails (developed in RFCS MINTOS project) it is also envisaged to interconnect the distributed location station subsystem developed in RFCS EMTECH project. First prototypes were also used during the final trials with multipoint measurement system (aerologic and machine monitoring sensors) developed in MONITOR&PREDICT project carried out by EMAG in the EUREKA programme.

#### 3.5.4.4 Software development

The managing software developed is needed to perform the network configuration, i.e. the software developed during the project for that purpose is also expected to be used in HUNOSA facilities.

### 3.5.4.5 Deliverables of WP 4

| Code | Deliverable | Type |
|---|---|---|
| D 4.1 | Prototypes of explosion proof, low power, FO Fieldbus electronic interfaces | Prototype |
| D 4.2 | Prototypes of explosion proof connector and cabling system | Prototype |
| D 4.3 | Communication and handling software | Software |

## 3.5.5 Underground testing (WP5)

No exploitation of the tests itself although the tests were indispensable prerequisites for the exploitation of the various development results. However, their exploitation is reported under 4.5.1 to 4.5.4.

### Deliverables of WP 5

| Code | Deliverable | Type |
|---|---|---|
| D 5.1 | Prototype of an operational Fieldbus system harmonised with the requirements of WP1 and WP3 | Prototype |
| D 5.2 | Final report and recommendations to industry | Report |
| D 5.3 | Testing full automatic shearer loader system | Prototype |
| D 5.4 | Testing of monitoring, visualization and controlling system | Prototype |

## 3.5.6 Survey of Results and their exploitations

| N° | Result | Type | WP/ task refe-rence | Description | IPP* | Exploitation* |
|---|---|---|---|---|---|---|
| 1 | IR sensor system for coal / rock boundary detection | D / AS | 1.2 | 2 Sensors including IPC and evaluation software for layer detection and ranging arm steering | NE[1] | Successful in use[1] |
| 2 | Radar based system for obstacle detection | D / AS | 1.2 | 77GHz dual-range radar for detection of obstacles in the shearer tramming trac and shearer overload including evaluation software | NE[1] | Successful in use[1] |
| 3 | Wireless sensor technology with ranging capabilities | AS | 1.2 | Location of an moving object relatively to 'known' objects tagged with reference nodes using triangulation techniques. The relative distance is calculated from measurements of the time required for data packets to travel between two wireless nodes | NE[4] | The technology can be exploited in two other RFCS projects and enables the successful implementation of a 2D tracking system for vehicles and personnel[4] |
| 4 | Load dependant shearer regulation | AS | 1.2 | To avoid overload the conveyor speed transferred and the load value is converted in the shearer loader control system to a reduction factor for the speed of the shearer loader. | NE[1] | Successful in use in many applications[1] |
| 5 | Shearer location | AS | 1.2 | Synchronization switches at the Shearer loader and magnets at the conveyor ends in combination with the measurement of the rotation of the driving through potentiometers provide a location with a precision of +/- 1cm. | NE[1] | Successfully invented in various mines[1] |
| 6 | Improved seamless WLAN roaming | S | 1.1 / 1.2 | Seamless roaming for shearer communication | NE[8] | Successfully in commercial use[8]<br>Cost for protection not in relation to additional profit gained by it. |
| 7 | Machine Gateway | AS | 1.2 | Network device to logically separate machine networks from mine networks, to assure seamless roaming and to enhance wireless communication reliability of the machine | NE[8] | Successfully in commercial use<br>Cost for IP protection not in relation to additional profit gained by it. [8] |

Type: D= Device, IR= Internal Report, PR= included in Publishable Report, A= Analysis, S= Software, AS= Application System

IPP (= Intellectual Property Protection): NE= Not eligible for IPP (e.g. because of basic research), PR= Protection/patent registered, PP= Protection/patent pending, PI= Protection/patent intended

***1** RAG **2** Golder RMT **3** MRSL **4** EMAG **5** KOMAG **6** UoC **7** AITEMIN **8** Embigence

| N° | Result | Type | WP/ task refe-rence | Description | IPP* | Exploitation* |
|---|---|---|---|---|---|---|
| 8 | Machine Server | AS | 1.2 | | NE[8] | Successfully in commercial use<br>Cost for IP protection not in relation to additional profit gained by it[8]. |
| 9 | 24 GHz SLR Radar sensor | D | 1.2 | ATEX approved commercial sensor for general obstacle and profile clearance detection | NE[2] | Commercial use possible, awaiting related projects<br>Cost for IP protection not in relation to additional profit gained by it[8]. |
| 10 | Numerial modelling methodology to analyse failure mechanisms of rock under mechanical tools | A | 2.1 | Numerical modelling methodology to analyse failure mechanisms of rock under mechanical tools | NE[2] | FLAC3D numerical modelling methodology to allow prediction of pick cutting forces, could replace laboratory testing.<br>Development completed at the end of the project, therefore not used. [2] |
| 11 | Database of drum lacings | A | 2.1 | Database of drum lacings | NE[2] | Used for the development of the software[2] |
| 12 | CAD Software | S | 2.3 | Software to create and analyse drum lacings to optimise effective cutting to reduce pick wear and machine down time due to excessive vibration | NE[2] | Used on site specific examples from the database[2] |
| 13 | Methodology for optimisation poorly performing cutting drums | PR | 2.3 | Methodology for optimisation poorly performing cutting drums | NE[2] | Used on site specific examples from the database[2] |
| 14 | Longwall system visualization and monitoring toolkit | S | 3.1 | Visualization and monitoring software | NE[2] | Commercialisation[2] |
| 15 | Thermal imaging camera | D | 3.2 | Prototype portable thermal imaging camera for mining applications | PI[4] | Commercialisation[4]<br>Certification[4] |
| 16 | Vibration, temperature, liquid presence/level sensors | D | 3.2 | Prototype wireless diagnostic sensors | PI[4] | Commercialisation[4]<br>Certification[4] |
| 17 | Enhanced wireless gateway/router | D | 3.2 | Prototype wireless gateway for harsh conditions compatible with FO transmission system | PI[4] | Commercialisation[4]<br>Certification[4] |
| 18 | Water in oil sensor | D | 3.2 | Prototype water activity sensor for online oil contamination monitoring | PI[3] | Commercialisation[3]<br>Certification[3] |
| 19 | Maintainability assessment toolkit | S | 3.4 | Maintainability assessment software | NE[3] | Commercialisation[3] |
| 20 | Fiber optic contact for mining harsh environment | D | 4.2 | Fiber optic contacts with beam expander | PI[7] | Used both mining and non mining applications where a high bandwidth communi-cation system is needed in a harsh environment. [7] |
| 21 | Mixed connector and cabling system | D | 4.2 | Connector and cabling system aimed for fieldbuses communication systems based on FO. | PI[7] | Installation of high bandwidth communication networks based on fieldbuses in mining applications. [7] |

| N° | Result | Type | WP/ task refe-rence | Description | IPP* | Exploitation* |
|---|---|---|---|---|---|---|
| 22 | Universal Interface | D | 4.3 | Universal FO interface for mining monitoring and control applications including harsh environment FO contacts and mixed cable. | PI[7] | Distribution of access points along various locations in mines. Product under ATEX certification process. [7] |
| 23 | uZIST WDM transmission interfaces | D | 4.3 | Fibre optical interface/access point module employing WDM technology | PI[7] | ATEX Certification [7]<br>Commercialisation [7] |
| 24 | Verification on developed monitoring and communication equipment | N/A | 5.2 | Test helped to verify the developed hardware and software and brought the information required for bugfixing and optimisation | N/A[7] | The observations and conclsions resulting form underground tests were taken into consideration in final optimisation of the developed devices[7] |

# 4 GLOSSARY

## 4.1 ABBREVIATIONS

| | |
|---|---|
| ATEX | EU Directives on “*Appareils destinés à être utilisés en* ***AT****mosphères* ***Ex****plosibles*“ |
| CAD | Computer Aided Design |
| CAN | Controller Area Network |
| CENELEC | Comité Européen de Normalisation Électrotechnique |
| CERCHAR | Centre d’Etudes et Recherches des Charbonnages de France |
| CPE | Chlorinated Polyethylene |
| CPU | Central Processing Unit |
| DLC | Diamond- like carbon (coating) |
| EMI | Electro Magnetic Interference |
| FEM | Finite Element Methode |
| FLAC | Fast Lagrangia Analysis of Continua |
| FO | Fibre Optical/ Fibre optic |
| GOF | Glass Optical Fiber |
| HCS | Hard Clad Silica |
| HTTP | Hypertext Transfer Protocol Overview |
| IPC | Industry Standard Personal Computer |
| IR | Infra Red |
| IT | Information Technology |
| LAN | Local Area Network |
| LED | Light Emitting Diode |
| LRR | Long Range Radar |
| LVDS | Low Voltage Differential Signal |
| MATELEC | *Salón Internacional de Material Eléctrico y Electrónico* – International Fair of Electric and Electronic Material |
| MCU | Micro Controller Unit |
| MIB | Management Information Database |
| NA | Numerical Aperture (= $\sin(\theta_a)$) |
| NETD | Noise Equivalent Thermal Distribution |
| NIOSH | National Institute for Occupational Safety and Health |
| MAKS-DBC | System for remote control and online diagnostic of shearer loader (product of EMAG) |
| OKO-1 | digital intrinsically safe video camera (prod. by EMAG) |
| PAN | Personal Area Network |
| PCS | Plastic Clad Silica |
| POF | Plastic Optic Fibers |
| PowerLine | Data communication using the power supply cable |
| PMMA | Polymethylmethacrylate |
| PTB | Physikalisch Technische Bundesanstalt (Germany) |

| | |
|---|---|
| PU | Polyurethane |
| PVC | Polyvinyl Chloride |
| RELIA-2000 | Control and monitoring system for mining applications by AITEMIN |
| ROI | Region of Interest |
| RSTP | Rapid Spanning Tree Protocol. |
| RS 485 | Standard definition of the electrical characteristics of drivers for use in balanced digital multipoint systems |
| SAM | **S**ynthesis and **A**nalysis of Mechanisms (simulation tool) |
| SCADA | Supervisory, Control and Data Acquisition |
| SLR | Side looking Radar |
| SMF | Single-mode Fibers |
| SNMP | Simple Network Management Protocol |
| STP | Spanning Tree Protocol |
| TelNet | Teletype Network |
| UCS | Uniaxial Compressive Strength |
| VCSEL | Vertical-Cavity Surface-Emitting Laser |
| VPN | Virtual Private Network |
| WDM | Wavelength Division Multiplex |
| WiFi | Ttrademark of the **Wi-F**i Alliance that may be used with certified products that belong to a class of wireless local area network (WLAN) devices based on the IEEE 802.11 standards. |
| WLAN | Wireless Local Area Network |
| WP | Work Package |
| XML | Extensible Markup Language |
| µZIST | Mikro Zintegrowany Iskrobezpieczy System Transmisji'<br>(micro) Integrated Explosion proof Transmission System |

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**WP1**


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# 6 APPENDICES

## 6.1 ADDITIONAL INFORMATION ON WORKPACKES

### 6.1.1 Automation of longwall equipment (WP1)

***Dropped Methods for Coal-Rock Interface Detection***

***Laser Induced Fluorescence (LIF)***
Coal and rock can be distinguished from each other by characteristic fluorescence spectra. The tests showed that a separation of coal and stone is possible by the LIF method. The development status of LIF sensors does however not permit to use them underground.

***Chisel Force Logging***
This technology is basically suitable for the differentiation of coal and rock. Due to the necessary mounting of the sensors at extremely stressed components like the chisels and the difficult signal transfer, the technology seems to be suitable only to a limited extent.

***Geo Electricity***
Polarization in the rock influences the frequency dependency of the specific electric impedance. Hence, changes in the rock can be detected not only by measuring the resistance, but also by investi-gating the said frequency sensitivity.
The basic applicability could be approved in underground tests: The horizon of the coal could be clearly distinguished from the surrounding rock and the depth could be measured. However, an exact positioning of the layer between two sensors was not satisfactorily possible as the accuracy was >10cm.

Furthermore it has to be considered that the trial was a static one only. The judgement therefore was, that this technology may only be developed with great effort. As the pilot survey already was very time-consuming, this technology was dropped with a view to the time schedule and cost involved.

***Natural Gamma Radiation***
Natural gamma radiation is used frequently for coal / rock interface detection and systems appropriate to underground mining machines are available at the market. The requirements for the use of this technology are relevant differences in the $^{40}K$ emissions of coal and stone.
Laboratory measurements were carried out with a handheld device at stone samples as well as in situ in a German colliery. Due to the slight percentage of clay minerals in the rock the measurements however did not yield a significant difference in radiation behaviour. That is to say that the intensity of the radiation is too low for the application aimed at.

***Optical Sensor***
The utilisation of reflection characteristics of coal and stone in the visible spectrum was taken into consideration. Reports and experience of earlier applications of an optical system mounted at a sliding shoe at a plough were analysed. The conclusion was that wear and pollution of the sapphire optical window which by nature has to be arranged in an extremely high stressed position caused serious problems in that plough application already. By this reason and as a sliding shoe goes even less with the extraction principle of a shearer loader the optical sensor was excluded from further considerations.

***Seismic Measurements***
At the seismic principle conclusions are drawn from the runtime of mechanically induced sonic waves. In a longwall the shearer drums generate such waves in the bedrock when cutting. They can be measured and analyzed at another location. For now the seismic principle was only exemplary tested and the leading suitability was established. To make this technology applicable an immense initial effort seemed to be necessary, as no suitable devices for a shearer application are available on the market. That is why this development was dropped, too.

***Thermal Performance***
Coal and stone absorb and dispense different values of energy in a given time interval. Hence, this effect can be used to distinguish coal and rock. A series of laboratory tests were basically confirmed thid. However, they also showed that it is difficult to achieve the necessary temperature resolution by existing means. It was also expected that the thermophile sensor produces a considerable noise level, comparable to the effect of the bolometer of a camera. That is why this technology was excluded from further considerations.

***Geo Radar***
Geo radar basically is a suitable method for coal / rock distinction. Detailed investigations revealed however that, for technical reasons, this method cannot be realised easily because the sensor needs to be in touch with the material to be measured. Hence, similar problems were expected as with the optical sensor. Although trials of a group independent from this project in an opencast mine showed promising results their approach didn't seem to be transferable to the underground longwall situation. That is why this method was dropped.

***IR Data Processing and Interpretation***
Recording, picture position correlation and the saving of the coal interface and roof detection data is initiated and executed by the control software of the IR camera and the corresponding software. The recorded IR data is then processed and converted into usable control information editing software on the IR IPC. For coal interface detection, the saved IR pictures are put together to one face image by the picture editing algorithms. To enable generation of the face image, a Region of Interest (ROI) is defined for every single picture in the picture editing operations.

The ROI's are then stitched to eliminate errors in the image structure. The face image is binarised, and line structures and the coal/ rock interface are detected, smoothed and output. In addition, line structures which do not belong to the coal interface but cannot be rejected by a stable picture editing criterion are detected. The execution of the picture editing operations is automated.

***Figure 6.1.1-1*** shows a face image put together by stitching single IR pictures. The camera had not been calibrated so that distinct stairway effects aggravate the evaluation.

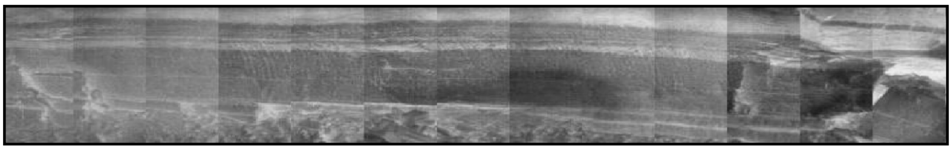


***Figure 6.1.1-1: Photographed sequence of the coalface***

The coal interfaces detected by the picture editing operations and further line structures consisting of several line segments are saved in a file and displayed as an overlay and in the form of single line segments as shown in ***figure 6.1.1-2.***

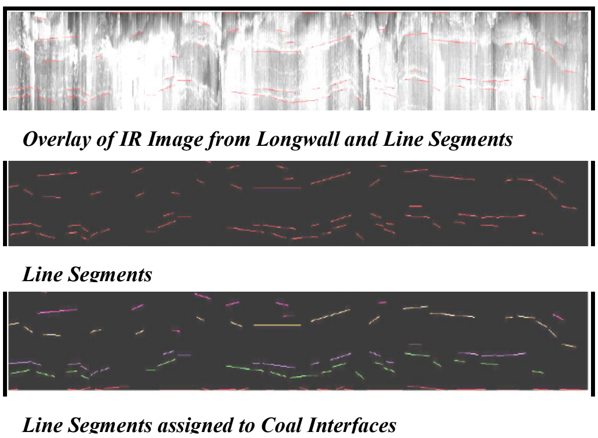



***Figure 6.1.1-2: Evaluation of the face image by picture editing operations***

These line segments and their coordinates (start point. Xs,Ys / end point. Xst, Yst) and lengths, are saved in a file. The individual line segments belonging to a corresponding coal interface are linked by appropriate intelligent algorithms. This is achieved by classifying lots of real data in order to extract previously unknown relationships and information.

The IR camera is linked to an Ethernet module via an LVDS plug so that digital video data can be detected without a frame grabber *(**figure 6.1.1-3, next page**)*. The Ethernet module converts the LVDS signal into a real stream. The Ethernet module is connected to the IPC via Ethernet module ports RJ45 which are linked by a CAT5 cable.

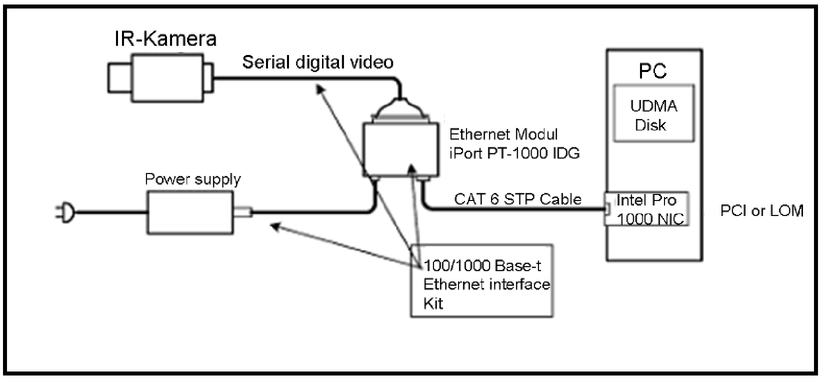



***Figure 6.1.1-3: IR camera connection scheme***

***IR Image Processing Algorithms***.
Out of different image processing programs tested such as HALCON, LABVIEW IMAQ and VISION WiT selected for its superior quick adjustment to changing longwall conditions.
During image processing, line detection is performed within the individual ROI only. To this end specific global edge transformations are utilized which are independent of the image information of the overall image. Adjoining operators detect changes and suppress any areas of constant grey values in the IR pictures. In this way a feature image is generated in which the changes appear bright whereas all other areas remain dark.

The algorithm for locating the edges is multi-stage: Firstly, edge enhancement is achieved by folding the edges using the derivative of a one-dimensional Gaussian function. The edge points are then combined into one edge configuration. To this end, all segmented pixels in the binary picture are classified and the local maxima determined from a starting point along the edge direction since the magnitude of the gradient also reflects the thickness of the edge. As a consequence, edges are found only at those places where the signal is considerably stronger than any potential effects caused by noise.

After the subsequent search for successor pixels, straight lines are detected and only those sections of the straight lines maintained in which a sufficient number of pixels is also set in the original image. The direction of the edge path can be derived from the gradient direction. If a pixel is part of an edge path, further edge pixels should be found orthogonal to the gradient direction First a mask is set and the edge pixel p is specified. The mask size depends of the angle of the line. Then the family of p is specified by directives that require the pixels to be within the mask and that they must be connected to p. ***Figure 6.1.1-4*** shows an example of such a detection.

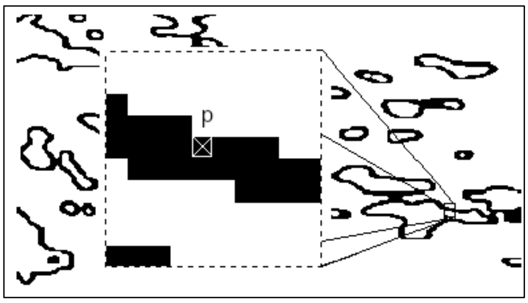



***Figure 6.1.1-4: Edge Detection and Classification Example***

The segments of the detected marker bands (white lines in ***figure 6.1.1-5, next page***) are assigned to the searched boundary layers with the aid of the survey data. The position-dependent Y-coordinates for every boundary layer are recorded in tables, and position lists of the boundary layers are prepared together with the information saved by the user in the input table.

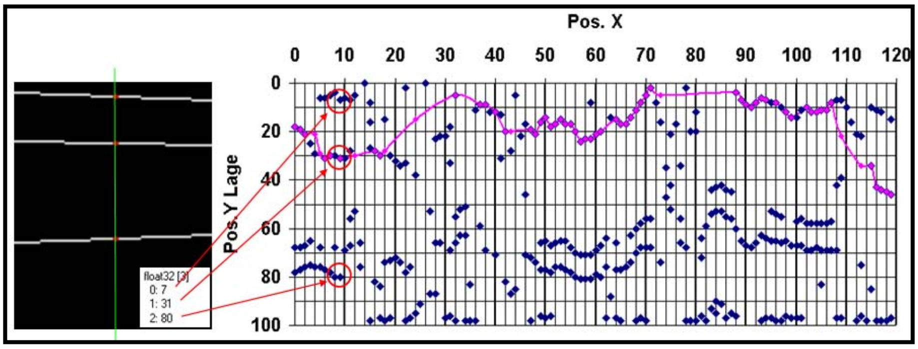



***Figure 6.1.1-5: Marker band detection (white lines) after image processing and boundary layer detection***

An evaluation of the bandwidth of the pictures is additionally implemented and generates a fault message as a function of the number of consecutive poor quality pictures. In order to avoid a negative effect on the evaluation of the raw data while providing a consistent reproduction of the longwall image at the same time, dummy pictures are inserted by the acquisition software in the case of picture loss and active spray automation.

During image processing, no line detection is carried out for the entire face image. Each individual IR picture is evaluated by the image processing algorithm. It is the strongest and most intensive texture of the leading layer that is being looked for. The obtained layer coordinates are transformed then into ranging arm adjustment target values which are transferred to the onboard control IPC where they are checked for plausibility. If plausible, they are used to replace the memory cut values. Additionally the IR system states are visualised to the shearer loader operator on the on-board display.

### *Radar Sensor for Obstacle Detection*

#### *Real Time Diagnosis and Raw Data Logging*

For diagnostics from the surface, the IPC software provides a status mask so that the principle of operation of the algorithm can be followed in real time via VNC client. Besides the status mask, the quantity of the algorithm calculated reflection clusters, the used intensity threshold, the face position in the array, and the tramming direction with a time and date stamp are written into a logging file making it possible to subsequently write a way- time diagram with the most important operating values of the algorithm into a file. The evaluation tool of the IR IPC saves the cluster raw data of the radar sensors enabling a simulation of different settings at the surface. Status information includes the sensor voltage for smooth operation monitoring and further status data for the system configuration, too.

#### *Data Processing*

As the radar produces more than 500MB/minute of raw data, a filter and communication module was developed. The firmware sends only key data on a CAN Interface. A data communication protocol between the machine PC and the radar PC was established. All basic parameters (installation inclines, etc.) are configurable by the service personnel. For this reason these values were saved on the IPC in an initialisation file rather than the program code. The parameters include geometric information such as evaluation range, radar height, installation incline, offset, tolerance bands, ranging arm geometry, etc. Various factors, threshold values and cycle times for fine adjustment of the algorithm are also saved in the file. To facilitate commissioning, help software containing a visualisation facility for the raw data was developed

Data processing on the shearer is executed by IPCs with real-time operating systems. For processing the sensor data by the radar IPC, external sensor data is needed made available by the onboard computer via Ethernet. This data includes the shearer loader incline in the tramming direction/pitch (inclinometer), the shearer loader position (odometer/absolute value transducer) and the tramming direction. The radar IPC is activated by the central computer. Differentiations are being made between the electrical commissioning, the model generation, the evaluation and the extent of control intervention. Moreover, only the radar which is in the tramming direction is activated to ensure optimum utilization of the scarce computation capacity. The data is archived for subsequent analysis and fault location.

***Machine Server***
The machine server comprises the following components:

- CPU module including a wired Ethernet port to connect automation systems on the machine
- Wireless LAN interfaces for communication with the in-longwall WLAN infrastructure.
- CAN card to connect the sensors.
- Antenna couplers for use of intrinsically safe external antennas

Special programs in the Machine Server and in the stationary Machine Gateway assure that the packets are forwarded to the clients in the right order and consistently as if there would be one single fully reliable hardware link. The Machine Server is also used to connect the IT level sensors to the Machine Network and to integrate video on demand as well as machine status web pages.

***Machine Related IT Functions***
A special focus was put on intelligent remote software download functions for the Machine Server and the machine gateway. Because of unsafe wireless connections to the machines, failsafe functions are implemented to provide a fallback to the "old" software and configurations in case the software / configuration download fails or the new software / configuration runs improperly: If a new software or configuration cannot be manually confirmed by a user using the web interface within a certain amount of time after rebooting the unit, the unit by itself will reactivate the old software (or configuration) and reboot on the old firmware which was known to be working. Thorough tests of these functions have been carried out.

Further functions include machine data management functions and auto diagnostic functions to enhance machine reliability and availability as well as to improve the usability of wireless LAN networks in the longwall. The aim of the machine data management functions is to prepare the Machine Server to provide usable operational information to external IT systems rather than unprocessed raw machine data. This information can e.g. be of operational character (on line information like status etc) or it can be used to assist in maintenance and operational planning (e.g. "Estimated time to next service" for single components etc.). As all information exchange today bases on web formats, the software is designed to use open external data exchange interfaces e.g. based on XML and Web services. These are also part of the "International Rock Excavation Data Exchange Standard", so a related information exchange will be using the principles of this standard even if profiles for coal mining machines do not exist in this standard yet.

***Network Security Functions***
In order to protect the machine from disturbances caused by other participants in the mine network, network security functions were implemented in the machine networking devices and in the machine server to securely block the shearer network from external networks. This prevents from unintended shearer faults caused by malfunctions or malconfiguration of external (mine) network related components. The shearer always shall remain functional as a machine even if the external network is not working.

The related functions designed for Machine Gateway and Machine server include filtering, running the network device on the shearer in a gateway mode and limiting access to the shearer using Virtual Private Network (VPN) connections. The machine networking devices are able to run all most recent network security features to cope with corporate regulations in terms of network administration and security.

As the networking devices are able to use the secure and encrypted VPN technology, also a secure Remote Access to the machine as e.g. by the machine manufacturer is possible without any influence on the mine network or other devices / equipment.

### 6.1.2 Optimisation of the cutting and loading process for Coal Shearers, Continuous Miners and Axial and Transverse Roadheaders (WP2)

No additional information

## 6.1.3 New methods for monitoring/diagnostic of machine operations/conditions, maintenance and maintainability (WP3)

*NEMAEQ SDA*

***Figure 6.1.3-1*** presents the main screen and a screen for logging to the software data base. The main screen enables selection of operation that the user can realize during running the software. The screen for logging to the software data base is a screen that enables logging to a selected knowledge database (in which parameters of the software are stored) operating on any database server

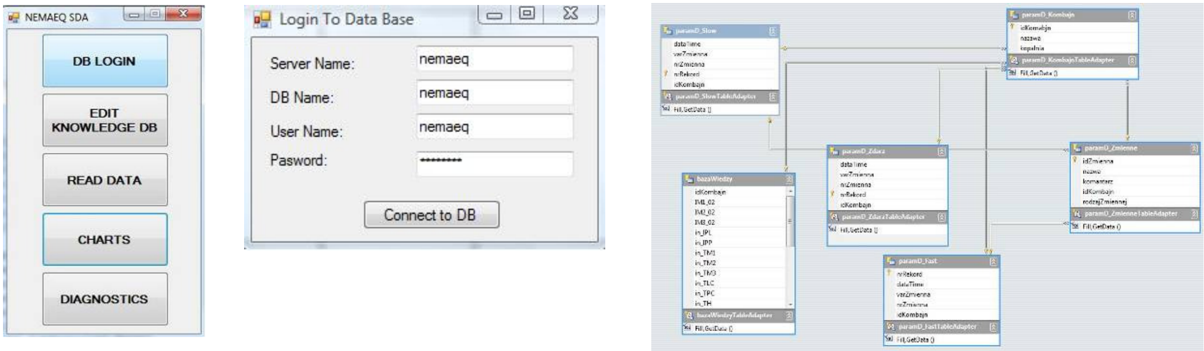



***Figure 6.1.3-1: Main Screen (left,) Login Screen (center) of NEMAEQ SDA and DB diagram (right)***

The Data base consists of 5 tables for storing measurement data and information on longwall shearer from which information is collected. The MS SQL Server authorization system is used for users' authorization. In the table "knowledge database" ("bazaWiedzy") information on parameters and failures that correspond to them are stored. Diagnostics of longwall shearer is carried out on the basis of information included in the table. Example data are given in ***table 6.1.3-1*:**

***Table 6.1.3-1: Example of shearer diagnostic data***

| Parameter | Unit | Parametr description | Monotonicity of time process |
|---|---|---|---|
| IM1_02 | [A] | Current of M1 motor | increasing very rapidly |
| IM2_02 | [A] | Current of M2 motor | increasing very rapidly |
| in_IPL | [A] | Current of M4 motor | increasing very rapidly |
| in_IPP | [A] | Current of M5 motor | increasing very rapidly |
| in_TM1 | [°C] | Temp. of M1 motor winding | increasing very rapidly |
| in_TM2 | [°C] | Temp. of M2 motor winding | increasing very rapidly |
| in_TLC | [°C] | Temp. of M4 motor winding | increasing |
| in_TPC | [°C] | Temp. of M5 motor winding | increasing |
| Advance | [m/min] | Shearer speed | decreasing |
| in_MO | [N*m] | Motor torque | decreasing |
| in_IP | [A] | Current of advancing motors | increasing |

***Table 6.1.3-2*** shows how monotonicity of time process was coded and what failures are to be detected.

***Table 6.1.3-2: Coding of monotonicity of time process and failures to be detected (right)***

| | | | |
|---|---|---|---|
| -2 | values of variables decrease rapidly | 3 | time process not determined |
| -1 | values of variables decrease | ANO | Failure is not specified |
| 0 | values of variables are not changing | ASOU | Failure of cutting drum motor |
| 1 | values of variables increase | APSOU | Failure of gear of cutting drum motor |
| 2 | values of variables increase rapidly | AOU | Failure of cutting drum |
| | | AOK | Failure of the shearer |
| | | AH | Brakes failure |
| | | AFO | Oil filter failure |
| | | ZSOH | Poor condition of oil in a hydraulic box |
| | | ZWS | Event in a longwall panel |
| | | AMP | Failure of shearer's advancing mechanizm |
| | | SCWK | Decay of water pressure in the shearer |

## 6.1.4 Data transmission by FO based Fieldbus-Systems (WP4)

No additional information

## 6.1.5 Underground testing (WP5)

***Final Tests of Automated Shearer (excerpts)***

***Functionality Demonstration of IR Control System***
Continuous use of the IR system over 10 metres of face advance
Test carried out 9th October 2009 at: Auguste Victoria Colliery, site 583
Cutting depth towards tailgate = 550 mm, towards maingate = 350 mm
Speed of the shearer loader: approx. 9 m/min

***Figure 6.1.5-1*** shows the test arrangement.

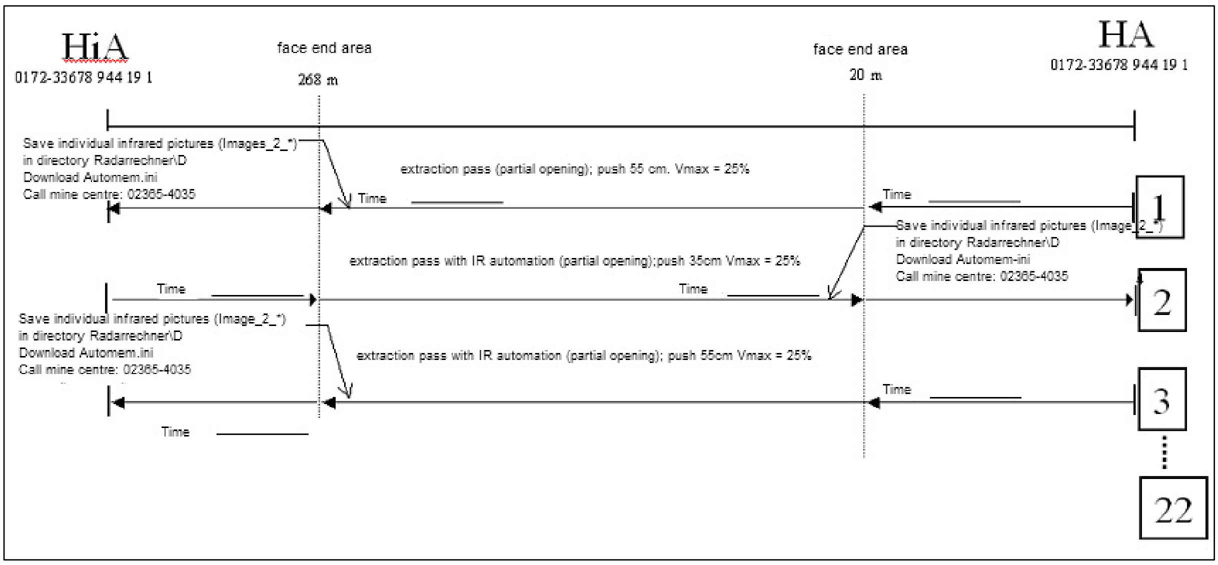



***Figure 6.1.5-1: Test arrangement***

For evaluation and documentation, the following parameters were recorded during the test:

- ranging arm heights
- the manual valve actuations of the ranging arms
- the gradient of the shearer loader
- shearer speed
- shearer position
- IR camera correction values of the shearer loader
- individual IR pictures
- the longwall images
- the adjustment target value tables
- the saved memory cut tables

In order to avoid scratching of the roof, the mine surveying details were adapted accordingly (200mm) so that the IR system guided the roof drum 200mm below the roof. Likewise, the mine surveying details of the floor drum were adapted for the undercut.

Examples of longwall images taken during the tests are given in ***figures 6.1.5-2 to 6.1.5-4:***

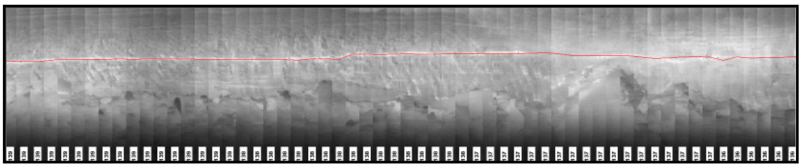


***Figure 6.1.5-2: Face section with well detectable leading layer Cut material is visible in the lower third of the longwall image (pass to maingate)***

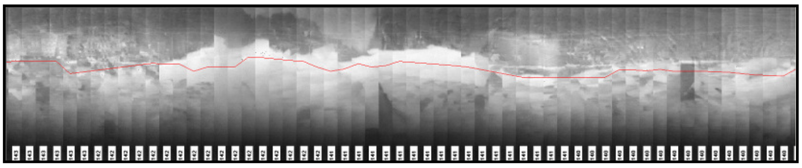


***Figure 6.1.5-3: Face section with poor detection due to strong emissions of the cut material Pass towards the tailgate***

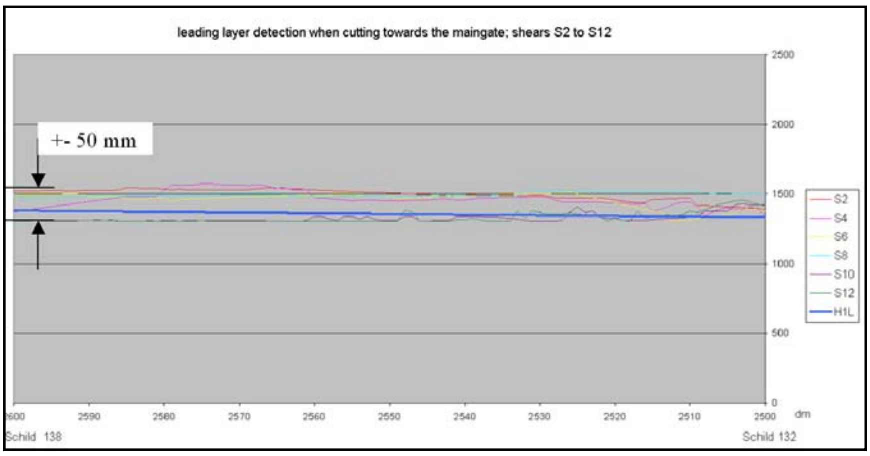



***Figure 6.1.5-4a: Automatic layer detection over several shears. S2-S12: H1L: mine surveying value, height between floor and leading. The layers could be detected constantly***

The comparison of the face height records before and after the tests reveals an undercut in the zone between shield no. 40 and 60 (marked in red in ***figure 6.1.5-5***, next page). This deviation is attributable to the poor quality of the IR pictures due to the fact that the leading layer was masked by material cut over several shears.

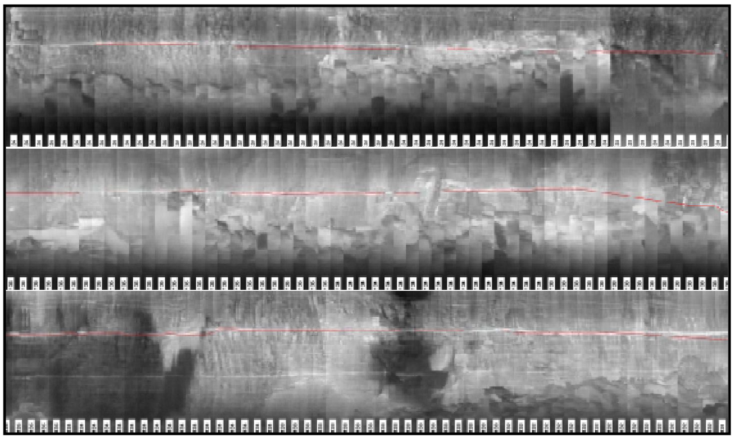
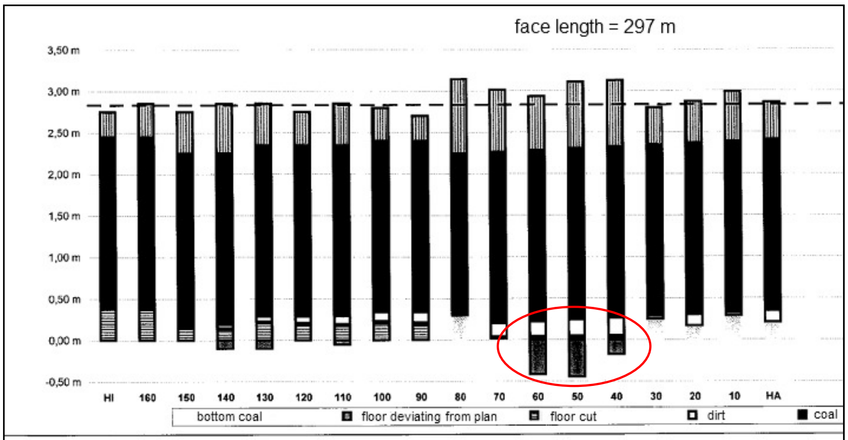


*Figure 6.1.5-4b: Associated longwall images. The sought leading layer is clearly detected by the image processing algorithm*




| Shield number | HI | 160 | 150 | 140 | 130 | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | HA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | **2,04** | **2,04** | **2,05** | **2,05** | **2,05** | **2,06** | **2,06** | **2,06** | **2,07** | **1,92** | **2,06** | **2,08** | **2,08** | **2,09** | **2,03** | **2,03** | **2,03** | **2,03** |
| Dirt in seam | 0,02 | 0,03 | 0,05 | 0,07 | 0,09 | 0,10 | 0,12 | 0,14 | 0,15 | 0,03 | 0,19 | 0,21 | 0,22 | 0,24 | 0,07 | 0,17 | 0,07 | 0,17 |
| Dirt in roof | 0,30 | 0,40 | 0,50 | 0,60 | 0,50 | 0,40 | 0,50 | 0,40 | 0,30 | 0,90 | 0,75 | 0,65 | 0,80 | 0,80 | 0,45 | 0,50 | 0,60 | 0,45 |
| Dirt in floor | 0,39 | 0,37 | 0,15 | 0,23 | 0,31 | 0,19 | 0,22 | 0,20 | 0,18 | 0,00 | 0,00 | 0,41 | 0,44 | 0,17 | 0,00 | 0,00 | 0,00 | 0,00 |
| deviating from the plan | | | | *0,10* | *0,10* | | *0,05* | | | | | *0,41* | *0,44* | *0,17* | | | | |
| Dirt in total | **0,71** | **0,81** | **0,70** | **0,90** | **0,90** | **0,69** | **0,84** | **0,74** | **0,63** | **0,93** | **0,94** | **1,27** | **1,47** | **1,21** | **0,52** | **0,67** | **0,67** | **0,62** |
| Seam thickness | **2,75** | **2,85** | **2,75** | **2,95** | **2,95** | **2,75** | **2,90** | **2,80** | **2,70** | **2,85** | **3,00** | **3,35** | **3,55** | **3,30** | **2,55** | **2,70** | **2,70** | **2,65** |

*Figure 6.1.5-5: Face height record*

The test revealed longwall sections where the shearer loader followed the seam line with great precision, but also zones where this could not be achieved. The evaluation of the positive zones yields a deviation of the machine position of ±50mm relative to the leading layer. All recorded shears were within this tolerance band. Deviations are found in zones with large quantities of material cut which either mask the leading layer or distract there from due to elevated temperature. During the execution of this test, this phenomenon resulted in undesired undercut. Given that the freshly cut "warm" material was wrongly taken for the leading layer, this tendency was amplified from shear to shear. A manual intervention from which was abstained deliberately in the test would have however corrected this effect easily.

The test demonstrated that the IR sensor brings about good results when the seam texture is well visible, and fulfils the requirements imposed on automation. In disturbed zones, however, corrections by the machine operator cannot be fully dispensed with.

### *Functionality Demonstration of the Radar Control System*

***Conveyor Overload Detection***

The zone for conveyor monitoring was dimensioned as follows for the test (***figure 6.1.5-6)***

- Start of the zone: 1,0 m in front of the radar sensor
- End of the zone: 2,0 m in front of the radar sensor
- Min. height of the zone: 0,8 m from the lower edge of the conveyor
- Max. height of the zone: 1,2 m from the lower edge of the conveyor

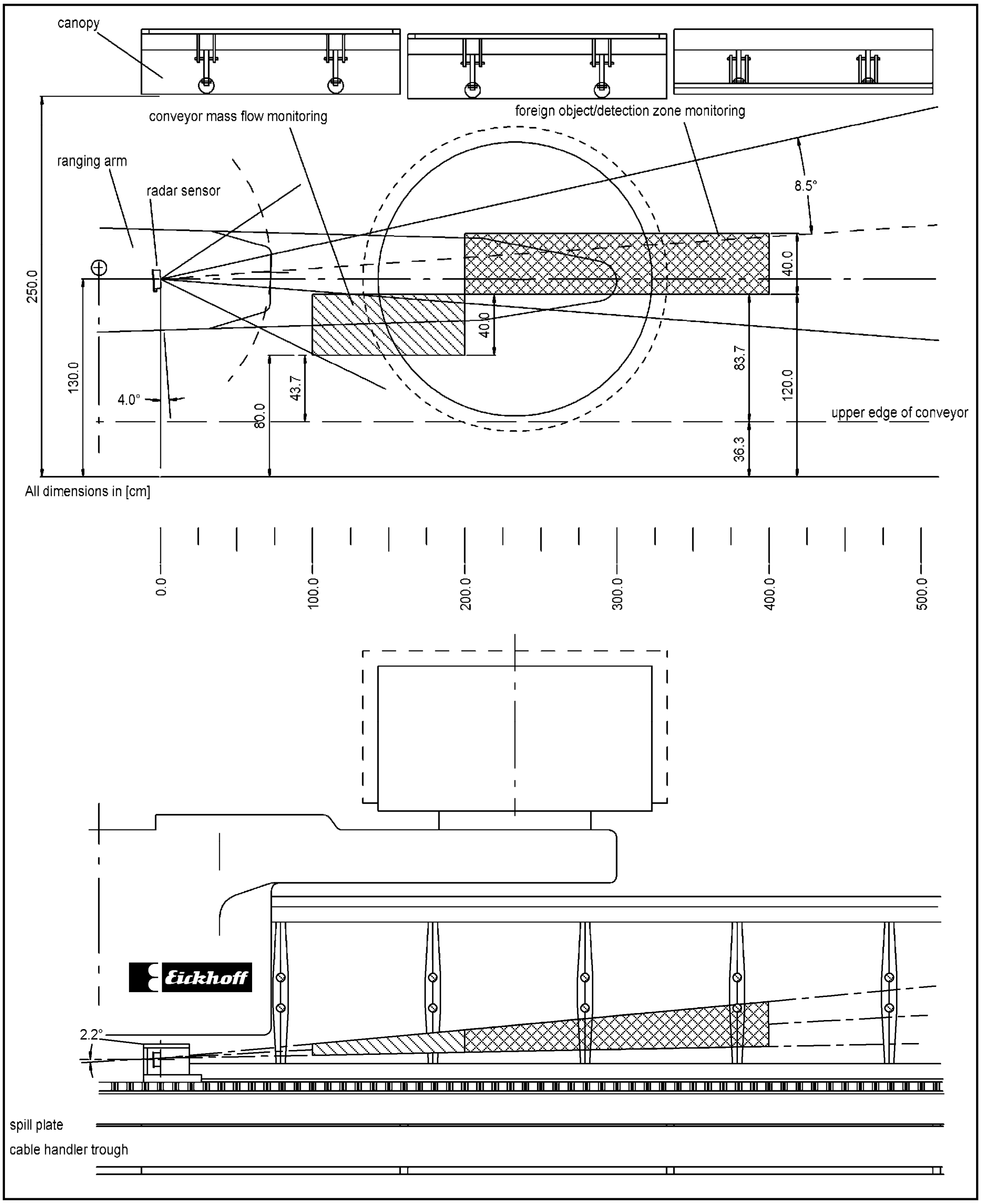



***Figure 6.1.5-6: Geometry of the detection zone for the tests***

Reference point for all height calculations is the lower edge of the conveyor. The area corresponds to the standard travelling track of the machine. Face ends are exempt from monitoring.

For the test a radar triple reflector was hung up above the conveyor and in front of the machine to simulate the overload. The height of the reflector measured approx. 1,16m from the lower edge of the conveyor. For the tests, the machine was moved starting at a distance of 8 to 10 m towards the obstacle. The test was conducted in three steps: The first step only included the detection of the targets and the spatial allocation to the machine coordinates. The next step was confined to the mere activation of the messages concerning the detected obstacles. Finally the control intervention was activated.

***Test Results Overload Detection***

- Objects / obstacles in the pre-defined monitoring zone are reliably detected and correctly displayed on the control screen,
- The geometrical allocation to and the distances from the radar sensor are correctly detected,
- Displays on the control screen are activated upon the detection of obstacles; a pop-up window with a corresponding message is generated,
- When the control intervention is activated, the machine controller reduces the haulage speed of the machine to the previously set value. The reaction occurs when the obstacle is approx. 2,0 to 1,5 m ahead of the radar sensor,
- After speed limitation has occurred, the machine can be speeded up by the operator using the radio transmitter. Upon detection of another obstacle, the speed reducing action is initiated again after approx. 15s.

The above results demonstrate the functionality of the "conveyor monitor" to the expected extent. Utilisation of this function can thus be released for normal mining operations.

***Obstacle Detection***

The zone for obstacle detection was dimensioned for the test as follows *(see **figure 6.1.5-6**, previous page):*

- Start of the zone: 2,0 m in front of the radar sensor
- End of the zone: 4,0 m in front of the radar sensor
- Min. height of the zone: 1,2 m from the lower edge of the conveyor
- Max. height of the zone: 1,6 m from the lower edge of the conveyor

The area corresponds to the standard travelling track of the machine. The face ends are exempt from monitoring. The general test arrangements were identical to the ones for conveyor overload detection except the height of the radar triple reflector which measured 1,36m above the lower edge of the conveyor.

***Test Results for Obstacle Detection***

- Objects / obstacles in the pre-defined monitoring zone are reliably detected and correctly displayed on the control screen,
- The geometrical allocation to and the distances from the radar sensor are correctly detected,
- Displays on the control screen are activated upon the detection of obstacles; a pop-up window with a corresponding message is generated,
- The machine is stopped ahead of the obstacle (haulage stop) when the control intervention is activated. This reaction occurs approx. 4,0 m to 3,5 m ahead of the active radar sensor,

- After the stop has occurred, the operator can continue moving the machine towards the obstacle by means of the radio transmitter. Such operator intervention releases a travelling path over one shield width which corresponds to 1,75 m. The machine is stopped again upon detection of another obstacle in the detection zone,

- Upon reversal of the travelling direction, the detection zone function is activated for the respective opposite side. The 1,75 m override zones are deleted each time the direction is reversed,

- When tested without radar triple reflector, the machine detects a lowered shield canopy protruding into the monitoring zone, and the machine is stopped when the control intervention is activated.

The results demonstrate the functionality of the obstacle detection to the expected extent. Utilisation of this function can thus be released for normal mining operations.

## 6.2 COMPANIES REFERRED TO IN THIS REPORT

| Company | Address | Telephone<br>Fax | Web |
|---|---|---|---|
| Atlas Copco Rock Drills AB | 105 23 Stockholm<br>Sickla Industriväg 3,<br>131 34 Nacka | +08 743 92 30<br>+08 743 92 46 | www.atlascopco.com |
| Bosch- Rexroth | Maria-Theresien-Str. 23<br>97816 Lohr | +49 (9352) 18-0<br>+49 (9352) 18-39 72 | www.boschrexroth.de |
| DEKRA | Handwerkstraße 15<br>70565 Stuttgart<br>Germany | +49.711.7861-0<br>+49.711.7861-2240 | www.dekra.de |
| DHMS<br>Deilmann-Haniel Mining Systems | Haustenbecke 1<br>D-44319 Dortmund | +49 231 2891 289<br>+49 231 2891 314 | www.dh-ms.com |
| Eickhoff (G.B.) Ltd | Darnall Works<br>Prince of Wales Road<br>Sheffield S9 4DZ<br>Great Britain | +44 114 261 0147<br>+44 114 244 9584<br>+44 121 683 1299 | www.eickhoff-bochum.de |
| Elastogran GmbH | Elastogranstraße 60<br>49448 Lemförde<br>Deutschland | +49 5443 12 0<br>+49 5443 12 2201 | www.polyurethanes.basf.de |
| Fundación Santa Bárbara | C/ Aguilonjos, s/n.<br>24310, La Ribera de Folgoso, León. Spain. | +34 987 52 30 69<br>+34 987 52 30 70 | www.fsbarbara.com |
| HSL | Harpur Hill<br>Buxton<br>Derbyshire SK17 9JN<br>UK | +44 (0) 1298 218000<br>+44 (0) 1298 218590 | www.hsl.gov.uk |
| HUNOSA | Avda de Galicia, 44<br>33005 Oviedo<br>Spain | +34 98 510 7300 | www.hunosa.es |
| ICP<br>(meanwhile closed) | C/Caracas, 33-35, Bajos A.<br>08030 Barcelona<br>Spain | +34 93 266 2768<br>+34 93 266 2389 | www.icpsl.com |
| LOM<br>Laboratorio Oficial J.M. Madariaga | C/Alenza, 1<br>28002 Madrid<br>Spain | +34 91 336 7009 | ./. |
| Moxa Europe GmbH | Einsteinstr. 7<br>85716 Unterschleißheim<br>Germany | +49 89 37003990<br>+49 89 37003999 | www.moxa.com |

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|---|---|---|---|
| NIOSH<br>National Institute for Occupatial Safety and Health | 626 Cochrans Mill Road<br>Pittsburgh, PA 15236<br>412-386-660.<br>USA. | | www.cdc.gov/niosh/mining |
| PTB | Physikalisch-Technische Bundesanstalt (PTB)<br>Bundesallee 100<br>D-38116 Braunschweig<br>Germany. | +49 531-592-3006<br>+49 531-592-3008 | www.ptb.de |
| Vaisala Ltd | Vaisala House<br>349 Bristol Road<br>Birmingham B5 7SW, UK | +44 121 683 1200 | www.vaisala.com |
| ZZM S.A.<br>Zabrzańskie Zakłady Mechaniczne S.A | 3 Maja 89<br>41-800 Zabrze<br>Poland | +48 32 271 32 31 9<br>+48 32 271 08 41 | www.zzm.com.pl |

European Commission

**EUR 24974 — New mechanisation and automation of longwall and drivage equipment (NEMAEQ)**

*J. Czwalinna, J. Kubik, D. N. Bigby, L. Kent, S. Bennett, C. Talbot, P. Wiszniowski, A. Piecha, D. Jasiulek, C. Sauer, A. Rodriguez, F. J. Espada Moreno, C. Müller*

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A fully automated coal shearer was developed with load-dependent regulation and coal/rock distinction through infra red and impact sound sensors. Collision avoidance is obtained through radar and video technologies. The development comprises appropriate control technologies and software for sensor data processing and a reliable integration of the onboard networks into the mine network.

The efficiency of cutting drums can be improved through FLAC3D numerical modelling to simulate the process of cutting, which can replace laboratory testing, and aid drum design. Specifically written CAD software can generate drum lacings to reduce pick wear and vibration-caused machine downtime. For determining the cause of poorly performing drums the software can be used as part of an iterative problem diagnosis process.

A novel monitoring and visualisation system provides analysis of longwall operations and equipment condition monitoring. Diagnostic devices developed include:

- a portable thermal imaging camera,
- wireless diagnostic sensors for online monitoring of triaxial vibrations, temperatures, leak detection and water in oil content.

A maintainability and human factors assessment software package was developed that will help to avoid or minimise practical difficulties and reveal options for maintainability improvement.

A fiber optic communication system was developed for 'the last mile', tolerant to the harsh underground environment. The flexible high bandwidth network provides support to any kind of mining monitoring and control system. It includes interfaces to integrate both new devices and legacy equipment. A dedicated software tool was developed for easy management of the network.

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