# INDIRES Newsletter

**Information Driven Incident Response**

**December 2020**

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Information Driven Incident Response

**Newsletter 3**
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Lack of information is a major hindrance to the effective response to a serious underground mining incident such as a fire, flooding, an explosion, or a fall of rock. INDIRES is a research project, the aim of which has been to allow the rapid acquisition of information and to permit communication between affected miners, rescuers and mine management. By improving the efficiency of mines rescue operations, it is expected that this initiative will help protect the welfare of personnel and the future operation and profitability of the mine.

INDIRES has been a three-year collaborative project. The interdisciplinary consortium comprises ten organisations from five member states of the European Union. Partners include two coal producers, three research organisations, three universities, a civil engineering consultancy and an equipment manufacturer.

**Front Cover:** Rescue Practice
**Back Cover:** Testing the Guidewire Rescue Communication System
**Photos:** Permanganic Velenje

This project has received funding from the Research Fund for Coal and Steel under grant agreement No 748632.

# The INDIRES Project: Practical Results

*As the project comes to a close, INDIRES Newsletter Editor **Mike Bedford** outlines the equipment and techniques that have been developed, and explains how they are a valuable resource for potential stakeholders.*

INDIRES is a research project funded by the European Union's Research Fund for Coal and Steel (RFCS). Standing for *INformation Driven Incident RESponse*, it has developed equipment and technologies to provide vital and timely information immediately after a serious mining accident. This will empower rescue teams to assure the safety of those personnel affected by the incident, and help protect the future of the mine.

This final newsletter is six months later than planned because the project was extended to cope with the COVID-19 pandemic. However, as we go to press, the in-mine tests of the equipment developed in INDIRES have just been completed. In this issue of the *INDIRES Newsletter*, therefore, we're taking the opportunity to summarise the project outcomes with particular reference to how these results can be used by stakeholders including mines rescue teams, mine operators, equipment manufacturers, research organisations and universities.

## Opportunities

The outcomes of this project fall into several categories. First, there are developments that are immediately available to end users. Included here are the software applications that (1) predict the environmental conditions in a mine during the evolution of a fire, and (2) predict the probable evacuation routes that miners will have taken.

Second, there is equipment that has been fully prototyped and tested. This, therefore, is available either for manufacture by the responsible partner or for licensing to manufacturers. Such equipment would then be available as a resource for mines rescue organisations. In this category are the electric transport vehicle for carrying rescue aids to the deployment region, and the composite material props that are intended for use in temporary rescue tunnels or excavations.

Third is equipment that has been prototyped but is considered a proof-of-concept so it is not ready for immediate use or manufacture. Opportunities exist, therefore, for research organisations, universities or others to carry out further development, perhaps in collaboration with a member of the INDIRES consortium. These opportunities are as follows.

The guidewire communication system is at a very late stage of development so the necessary further work is mostly a straightforward electronic design exercise.

The challenging and novel software associated with the team of robotic vehicles has been successfully demonstrated so completion mainly involves further environmental adaptation of the robots.

The work on the torsoinal drilling rig has produced detailed design documents which could form the basis for prototyping and testing, leading to manufacture.

And the through-the-earth communication system and the closely associated resilient survivable sensor are considered proofs of concept although the significant amount of research work carried out in the project clearly show a route to finalising the design.

## User Documentation

In this *Newsletter*, we highlight several pieces of equipment and techniques that have been developed, and which are now available for use, exploitation, or further research and/or development. Although this will allow potential users, manufacturers or researchers to identify areas of interest, it will not be sufficient to allow stakeholders to take the next step in using the results of the INDIRES project. For this reason, an important project outcome that you need to be aware of is the *User Documentation* that is being made available to prospective stakeholders.

This *User Documentation* has been prepared as several separate documents, one for each type of equipment or technique, each providing the detailed information that is essential for potentially interested parties.

In the case of developments that are now available for end users, the user manuals will provide detailed information on how to use the equipment or technique. In the case of equipment that is suitable for licensing to manufacturers, sufficient information on the design and use of the equipment will be provided to allow a potential manufacturer to take a first step in assessing the opportunity. And for equipment that has been taken to the proof-of-concept stage, again information has been provided to help research organisations to appraise the opportunity. In each of these cases, the *User Documentation* will provide contact information within the responsible partner organisation so that the various opportunities can be discussed in more detail.

The *User Documentation* is available from any of the project partners and it is also being put on the project website at INDIRES.EU.

## The Next Step

The people who have been involved in INDIRES have taken a good deal of satisfaction from the outcomes that have been achieved. But that isn't only because the work has been interesting and challenging. It's surely also true that the professionals involved appreciate the beneficial nature of the results and recognise that lives could be saved as a result of the project outcomes.

Although this is undoubtedly true, as the INDIRES project now comes to a conclusion, it is now down to the various stakeholders to take these developments forward in various ways, whether that's as end users, as manufacturers or as researchers and developers. As we aim to hand over the baton to end users, manufacturers and other researchers, though, it's important for us to stress that the project partners will continue to be available to support you in the next stage of exploiting the results of the INDIRES project. We look forward to hearing from you.

# Lightweight Composite Props for Supporting Rescue Tunnels

*To support the creation of temporary tunnels for use during a rescue, roof supports comprised of a composite material have been developed for improved manoeuvrability by rescue teams.* ***Wojciech Masny*** *and* ***Aleksander Wrana*** *of GIG and* ***Grzegorz Plonka*** *of PGG report.*

As a result of underground accidents, mine workings may collapse. In order to safely reach the miners in such a hazard zone, sometimes it's required to drive a new heading. This may be quite complicated especially due to rock debris, damaged parts of the supports, and underground equipment. The main task of a rescue tunnel support is protection of the roof to ensure the highest possible safety of rescuers and miners. In carrying out a rescue action, props are used as both, direct and indirect support for the roof as well as rock waste when an emergency heading is driven.

## Requirements

There are several specific requirements for a rescue tunnel support:

- provide effective stabilization of newly driven rescue heading,
- high strength of components but low mass,
- ability to perform bend (avoiding obstacles e.g. damaged heavy equipment),
- quick and easy installation resulting in rapid advance,
- possibility to change the dimensions on different sections.

The main type of rescue tunnel support is wooden with straight beam and two legs. The main advantages of this support are very easy installation, easy wood processing (adaptation of dimension for conditions), low mass and availability. But the wooden support has disadvantages too, mainly the lack of setting force and the need to accurately process the ends of the legs at the connection with beam. Also steel support elements are used by rescue teams (friction, hydraulic and pneumatic props). Steel props have higher bearing capacity and act as active support with setting force (hydraulic and pneumatic props). The main disadvantage is the weight of the steel elements.

## Design & Testing

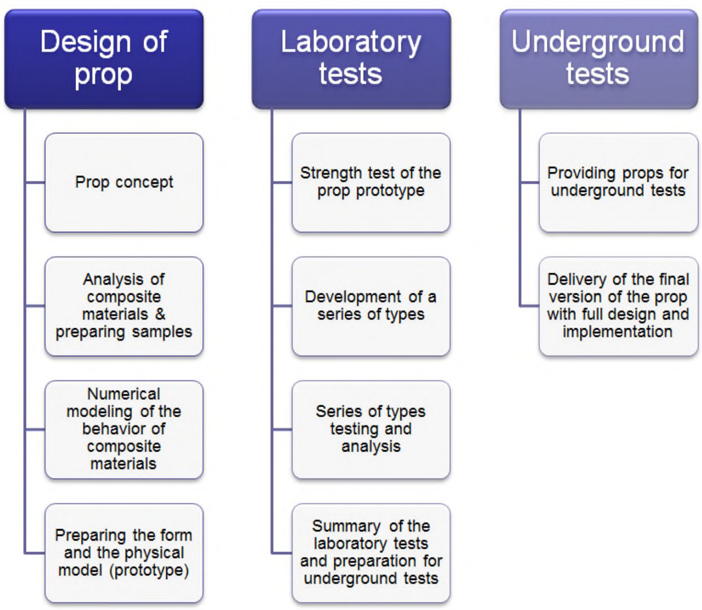
Considering the abovementioned, the work on a composite material prop as a part of a rescue tunnel support has been undertaken. A comprehensive overview of the design process is shown in the diagram at the bottom of this page. The design process was described in more detail in the second *INDIRES Newsletter*.

The most important stages of the project were laboratory and underground tests, where the design assumptions were confirmed. These are both illustrated at the top of the next page. In both these strands of testing, the main goals were as follows:

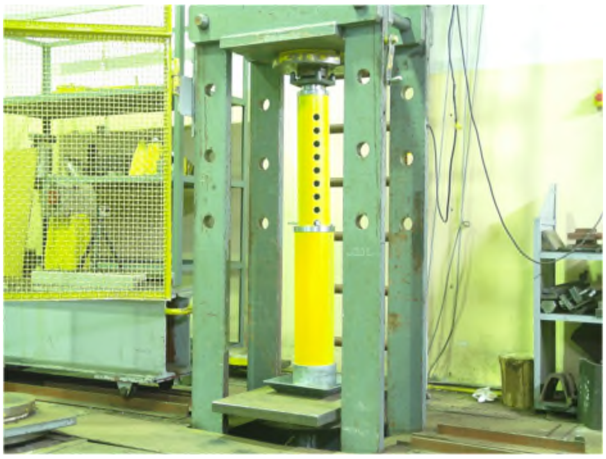
- stability of the prop prototype,
- deformation of elements (pipes) made of composites,
- deformation of steel elements,
- connections between steel and composite elements,
- the possibility of buckling,
- the strength of the bolt, also in terms of the material used,
- the maximum deformation.

During the laboratory tests no damage was observed in the composite material prop. In particular, the connection between the composite material and steel elements, especially the reinforcing structure, was not damaged. The prop subjected to the tests showed no tendency to buckling and other

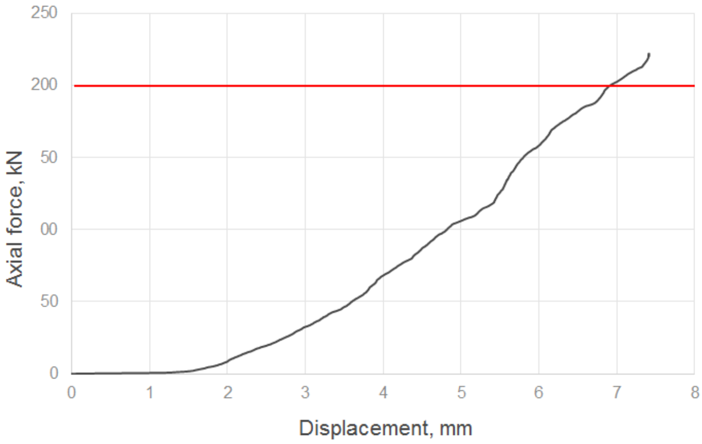
*Prototype Composite Props.*



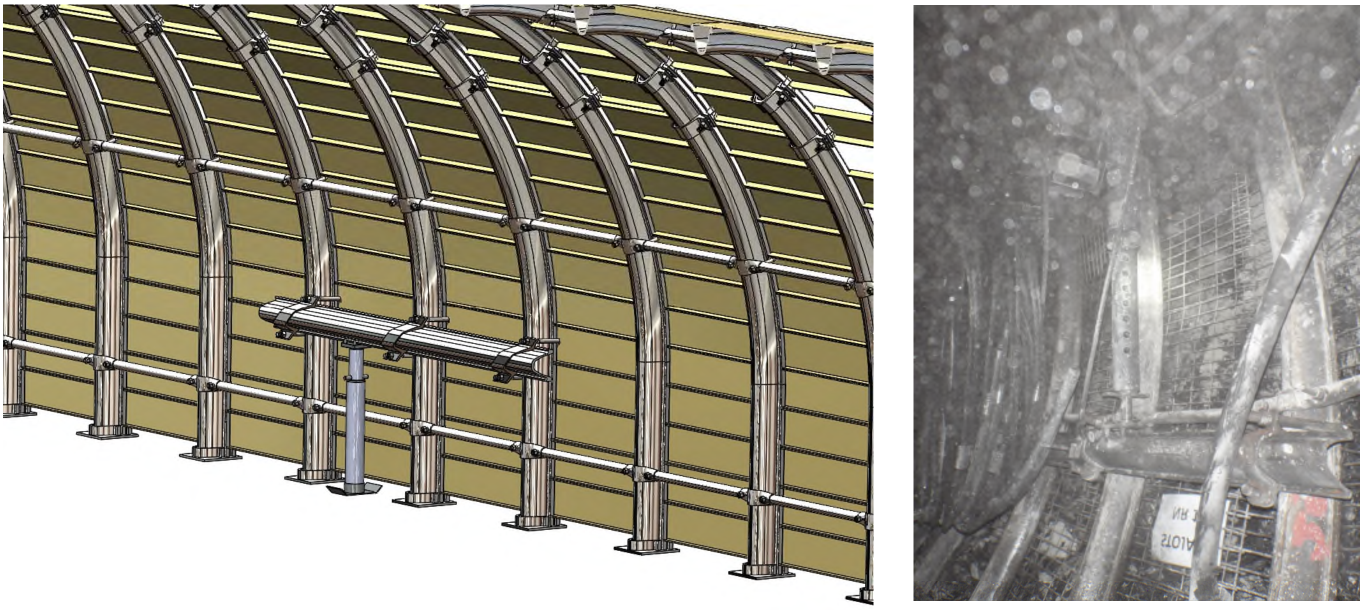

*Overview of the design process.*



Composite prop testing in hydraulic press.




Displacement vs. axial force characteristics.



Underground test conducted in a longwall gate road.

deformation. The maximum load bearing capacity of the composite material prop was > 220kN.

The composite material from which the prop was made was tested for antistatic and non-flammable properties. Both these tests gave a positive result. The material was shown to be non-flammable, and the surface resistance, $R_s$. was less than $10^9\Omega$.

The under-ground test confirmed the possibility of using the composite material props in the difficult conditions of underground mines, related, among others, to the presence of dust and humidity. The value of the recorded axial force was even greater than in the laboratory tests, at 313.5kN.


Exhibition stand at International Fair of Mining.

## Outreach

The composite material prop was presented to potential interested parties during the International Fair of Mining, Power Industry and Metallurgy in Katowice, Poland. This is Europe's biggest mining exhibition with over 400 exhibitors from 19 countries. The official presentation was possible because the solution of the prop was submitted to the Polish Patent Office.

Moreover, the composite material prop was positively acknowledged at the International Warsaw Invention Show IWIS 2019, where the design team was awarded a bronze medal.

The main goal of the work carried out by GIG in the framework of the INDIRES project was to develop a composite material prop that met the two requirements of low weight and adequate load bearing capacity to assure the safety of working rescue teams. It appears that both of these basic requirements have been met.

# A Guidewire Communication System for Temporary Rescue Use

*A communication system for use along mine galleries, which is capable of working around bends and through obstacles, has been developed. **Mike Bedford** of the University of Exeter and **Angel Rodríguez** of Universidad Carlos III de Madrid describe the system and provide the results of an experimental evaluation.*

An emergency communication system has been developed for use in a mine rescue situation when the mine's normal networks are inoperable. The system operates along galleries but it is not adversely affected by bends or obstacles that would make normal radios unusable. It operates using a cable – with is laid along the gallery by the rescue team – that guides the signal. This is one of two communication systems developed in INDIRES. The other operates through the rock and is described elsewhere in this *Newsletter*.

Although guidewire systems have previously been produced for rescue use, the system described here offers unique benefits. Previous guidewire systems either required rescuers to hold their handsets very close to the wire or to fit periodic Bluetooth repeater units which allowed communication within a few metres of that repeater. The INDIRES system, on the other and places no such constraints on users. In particular, rescuers can use the system from a distance of several metres from the wire. This means that communication does not interfere with other actions and, for example, rescuers are able to communicate while they are walking along a gallery.

## A Leaky Feeder Approach

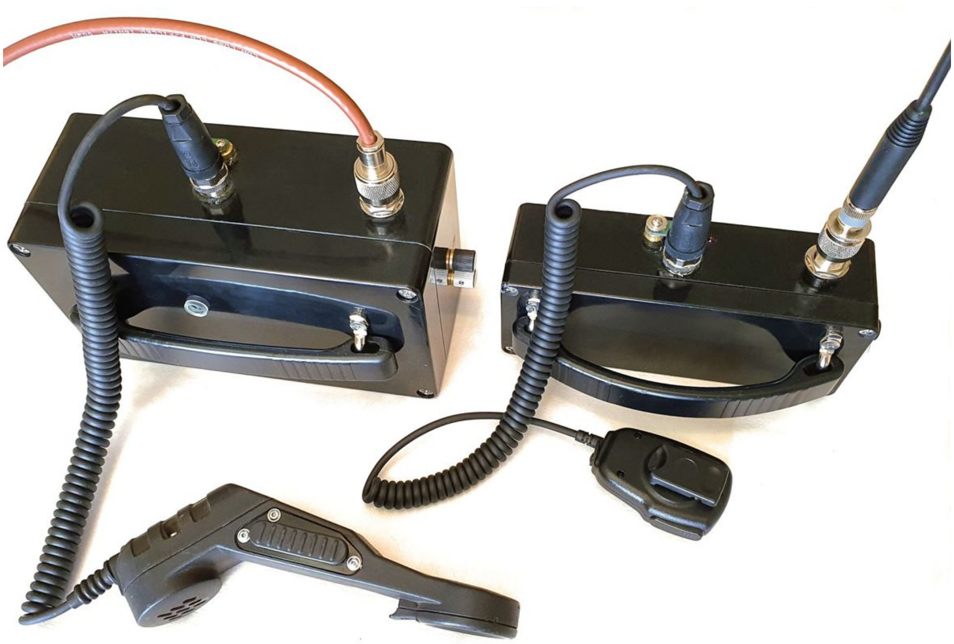
The guidewire system operates in a similar way to the leaky feeders that are used in transport tunnels and some mine galleries. However, it has one very important difference. Leaky feeders are a special type of coaxial cable, the type of cable that is often used to connect an antenna to a TV. However, ordinary coaxial cable is designed to transmit as much signal as possible from one end of the cable to the other, but a leaky feeder is designed to allow some signal to leak both in and out. However, to compensate for this loss, and therefore allow an acceptable amount of signal to progress along the cable, the cable often has a significantly greater diameter than ordinary coaxial cables and it is, therefore, much more expensive. Typical leaky feeders are 16mm - 50mm in diameter, they weight 220kg – 1,120kg per kilometre, and they cost thousands of pounds per kilometre.

The cable specified for the INDIRES system is not designed as a leaky feeder. Instead, it is a low-cost cable designed for use with TV antennas. But because it is a low-cost cable, it is a poor performance cable and, specifically, it was found that it leaks signals in and out. For its intended application this is not desirable but for use as part of a guidewire system it is ideal. In fact, tests showed that, at an optimal frequency, it provides a very good compromise between leaking some signal in and out while allowing sufficient signal to continue along the cable. Most importantly, though, this cable has a much smaller diameter than proper leaky feeder, it is lighter, and it is very much less expensive. This latter point is important. A cable laid quickly along a mine gallery during a rescue action is likely to suffer damage due to rock falls, people walking on it etc. For this reason, it cannot be relied upon to work correctly in a future rescue so it should be discarded after every use. For this reason, only a low-cost cable would be suitable.

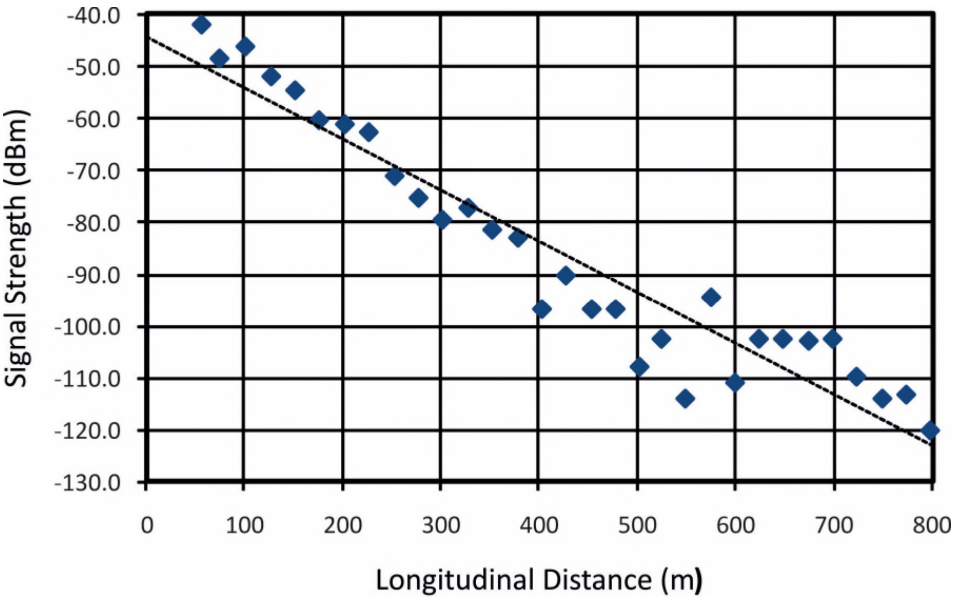
## The Handsets

Preliminary tests in the INDIRES project revealed that the optimal frequency of this system is just below 30MHz which is in the HF portion of the radio spectrum. Conveniently, CB radios, which can be used legally in most countries, operate on 27MHz and are readily available at low cost. Accordingly, standard CB radios were used in the experimental verification.

For operational use in a non-coal mine, off-the-shelf CB radios could legally be used although more rugged units would be preferable. For use in coal mines, such radios could be re-housed in ATEX compliant enclosures and such a technique has been demonstrated in the INDIRES project – see photo below. Alternatively, because the radio circuitry is conventional



*Typical Guidewire Base Station and Handheld Radios*
*These radios were based on off-the-shelf CB radios, re-housed in ATEX enclosures but other options are possible.*




*Signal strength tests showed an attenuation rate of 10dB per 100m.*

– even though the way the radios are used is novel – it would be feasible for user organisations to commission the design of suitable handsets and obtain the necessary ATEX certification.

## Field Trials

Field trials of the guidewire system took place in two phases. First of all, tests were conducted in the underground service tunnels at Universidad Carlos III de Madrid. This phase of testing was carried out by engineers who had developed the equipment so the opportunity allowed various measurements such as signal strengths to be made, as well as conducting normal speech tests.

The second set of tests was carried out in the Velenje Coal Mine in Slovenia. Because of COVID-related travel restrictions, the engineers who had designed the system could not be present. The tests were, therefore, conducted entirely by mining engineers and rescue personnel.

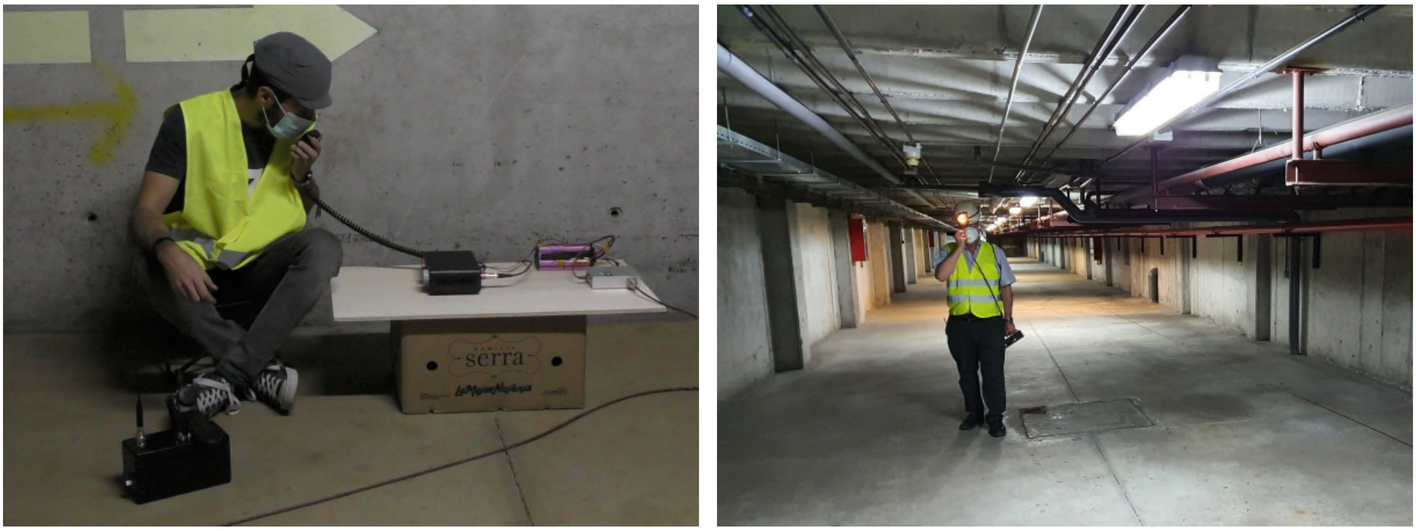
## Results at UC3M

The first phase of testing involved connecting a base station to the cable and measuring the signal strength along the cable using a receiver at a fixed distance from the cable. These tests showed that the average level of attenuation was 10dB/100m, and a useable signal strength was present to a range of 800m. As the end of the cable was approached, peaks and troughs were noticed in the signal and, at a few points, the signal was at the level of the background noise. This is not considered a major problem from an operational viewpoint because it was necessary only to progress a further metre or so to regain the signal. Also, tests of signal strength against separation between the handheld unit and the cable showed that approximately 10dB was in hand, suggesting that the maximum range would be 900m at the expense of having to hold the handset closer to the cable towards the end of the line, at some points.

In many cases, an operational range of 800m will be sufficient to bridge the gap between the area in which rescue operations are taking place and an area in which the permanently installed communication system is operational. However, in instances where a greater range is needed, several options are available. More information is available in the *User Documentation*, but it is estimated that the range could easily be extended to over a kilometre by making some incremental changes to the equipment.

Another option, but at the expense of having to carry and install additional equipment, is to use an in-line amplifier which would be connected to the cable at a point at which signals from the base station are easily readable. Then, a further length of cable would be run after the amplifier, thereby almost doubling the range. Further improvements could be achieved using additional amplifiers. If the power of the amplifier is limited to around 6W, each amplifier and its associated battery would be compact and light, thereby allowing it to easily be carried to the required location.

Speech tests – which were carried out both in the service tunnels and the colliery – confirmed these measurements. Voice communication between a hard-wired base station and a mobile handheld radio was possible to a range of 800m in the UC3M tunnels, which was the maximum length of tunnel available. The range between two handheld radios was 650m but this could be increased using a store-and-forward facility in the base station. In



*Speech tests in the service galleries at the UC3M campus provided good communication over 800m.*


*Tests of the guidewire system in the Velenje Coal Mine showed its suitability for rescue communication.*

this case, messages transmitted by a handheld unit would be recorded and re-transmitted by the base station for reception by any other handheld radios.

## Results at Velenje

Tests at the Velenje Coal Mine were carried out in three stages: initial surface tests for familiarisation with the equipment, underground testing, and practical use underground with the mine rescue team.

One part of the team was always located at the base station transceiver. The other part of the team, equipped with a hand-held transceiver, was moving along the gallery where the leaky feeder cables were installed and along the galleries connected to that gallery.

Audibility was good along the entire length of the leaky feeder cable, even at the total final cable length of 800 meters. Communication was then tested in the galleries connected to the gallery along which the leaky feeder cable was installed. As would be expected, the signal availability depended on the distance from the leaky feeder cable, and also on the angle at which the individual gallery was connected to the gallery in which the cable was installed. However, along these six galleries, communication was achievable at points that were 67m, 115m, 53m, 74m, 42m and 82m from the leaky feeder cable. In addition, it was shown that the equipment allowed communication to a distance of 300m in straight galleries, even if the leaky feeder was not installed.

Speech intelligibility in the phase three tests was reduced somewhat because the participants were using breathing apparatus. It is recommended, therefore, that to increase speech intelligibility, it would be necessary to use a microphone built into the breathing apparatus mask and connected directly to the hand-held transceiver.

*Cable installation in the Velenje Coal Mine.*

## Current Status

Because the guidewire communication system described here was fully prototyped and tested in a mine environment, the information provided in the *User Documentation* could be utilised by end users who have a need for the exact functionality provided by the INDIRES prototypes. Such users can consider the instructions in the *User Documentation* on how to use the guidewire equipment as definitive.

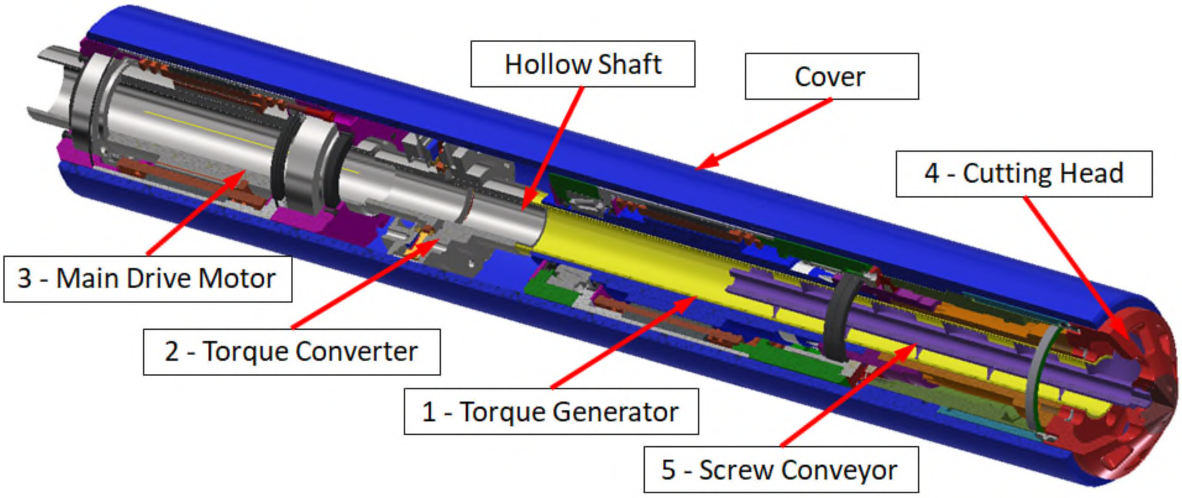
It is important to recognise, though, that the prototypes made use of commercially available CB transceivers, that were re-housed in ATEX certified casings to permit their use in coal mines, although some further work, mostly on the power source, would be needed to allow ATEX certification. The same approach could be used for organisations requiring just a few units.

However, organisations needing a larger number of units will almost certainly prefer to develop, or arrange for a third-party to design and develop, their own units that could then be manufactured in volume. Because the radio equipment is conventional – only the way in which they are used with the low-cost leaky feeder is novel – such an electronic design would not be onerous, although the issue of ATEX compliance should not be under-estimated. Information provided in the *User Documentation* will, therefore, also be relevant to organisations who intend to develop their own equipment that can be used in the guidewire communication system. End users or developers who want to know more, and perhaps to discuss possible collaborative opportunities, are referred to the *User Documentation*.

# A New Concept in the Design of a Drilling Rig for Rescue Use

***Tomasz Trawiński** and **Marcin Szczygieł**, scientists from the Silesian University of Technology in Poland, have developed a new type of drilling rig. This novel concept uses torsional vibrations in the drilling process at frequencies close to the natural frequencies of the material being cut.*

As part of the INDIRES project, partially by the Silesian University of Technology, by a team of scientists from the Department of Mechatronics, we designed a new, innovative type of drilling rig which will be used for creating rescue tunnels. The new drilling rig consists of three main components: an electromagnetic torsional vibration generator, a torque converter, a drive motor and an internal screw conveyor and cutting head. The diagram above shows the drilling rig: (1) is the torsional vibration generator, (2) torque converter, (3) main drive motor, (4) cutting head and (5) screw conveyor. The drilling rig system can be divided according to the operating speed of its components, namely the high-speed area and variable speed area. The main drive motor works in the high speed area, it generates the main drive torque for the cutting head and, at the same time, it drives the internal screw conveyor. The induction torque converter operates between high and variable speed areas, and is responsible for the non-contact transfer of the drive torque for the torsional vibration generator and cutting head.

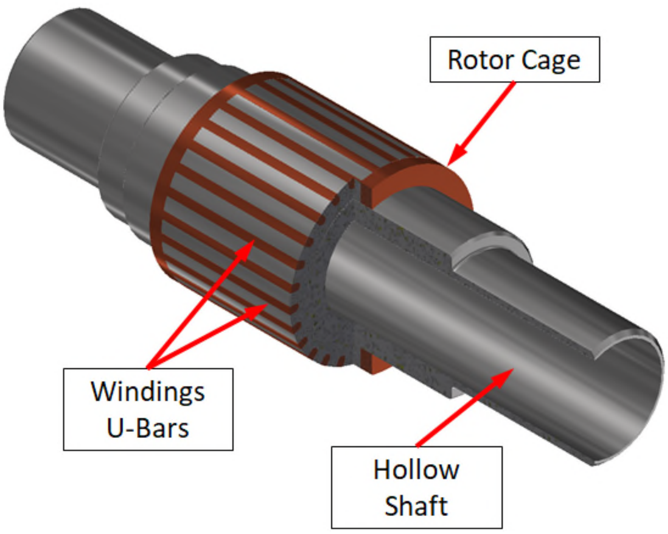



*View of Cross-section of Drilling Rig*

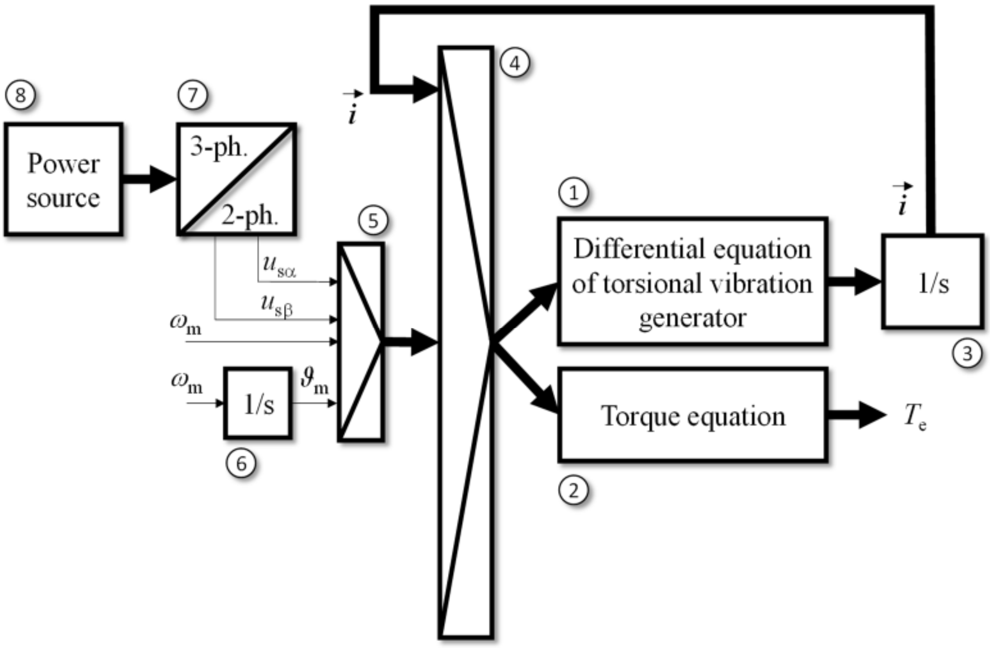
## Electromagnetic Torsional Generator

In addition to mathematical field models and construction drawings for the torsional vibration generator, systems of differential equations were also formulated to allow the analysis of various dynamic states of the generator. They allow for the analysis of the generated instantaneous torque waveform as a function of the rotational speed of the rotor. It is also possible to study the influence of the supply voltage frequency on the harmonic content at the moment produced by the torsional vibration generator. A very important feature is the ability to analyse the influence of changes in the generator rotor rotational speed and the voltage frequency and the amplitude of the generator supply voltage on the value of the generated torque and its harmonics.

The general scheme for solving the electromagnetic torsional torque generator is shown on the next page. This scheme allows for convenient implementation of the mathematical model in modern computer software like Matlab or Scilab. In block 1 the left side of ordinary differential equations which describes the dynamic behaviour of the stator and rotor currents is written, the torque equation is written into block 2. In block 3, differential equations are



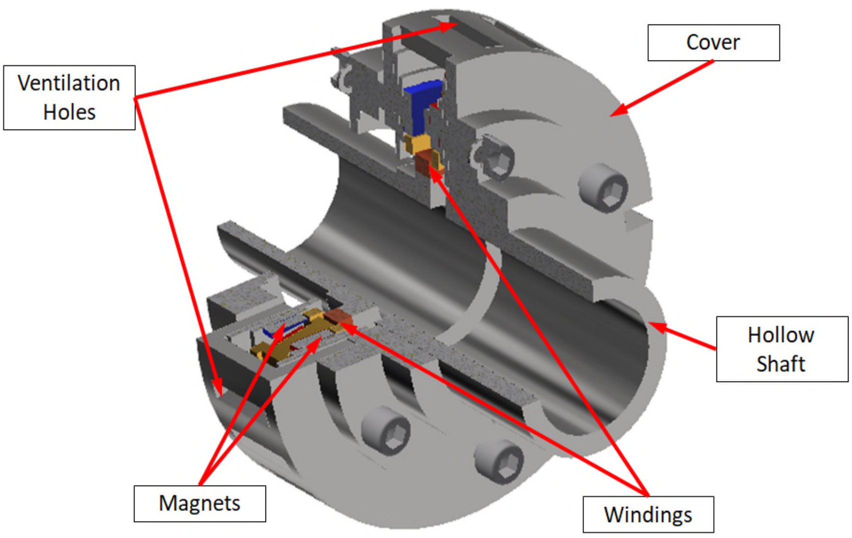

*View of Cross-section of Rotor of Torsional Torque Generator* integrated, and the results of the integration go to the multiplexer – block 4, because these results are necessary for the next step of the integration process. To the block 4 multiplexer there also enters the vector established by the multiplexer block 5, which consists of the stator voltage vector in the αβ-coordinate system and angular speed and the angular displacement (block 6) of the rotor. The power source voltages are covered in block 8, and those voltages which are represented in the natural 3-phase coordinate system are transformed by a Clark-Park transformation in block 7 into the 2-phase coordinate system. The developed mathematical model of the torsional vibration generator in the form of ordinary differential equations will also be useful in the process of developing the drilling rig control systems. These systems can be based on standard methods with scalar or vector control. But it seems tempting to develop a generator control method that ensures the desired torque harmonic content at a constant drilling speed.




*Mathematical Model of Electromagnetic Torsional Vibration Generator [2]*

## Induction Torque Converter

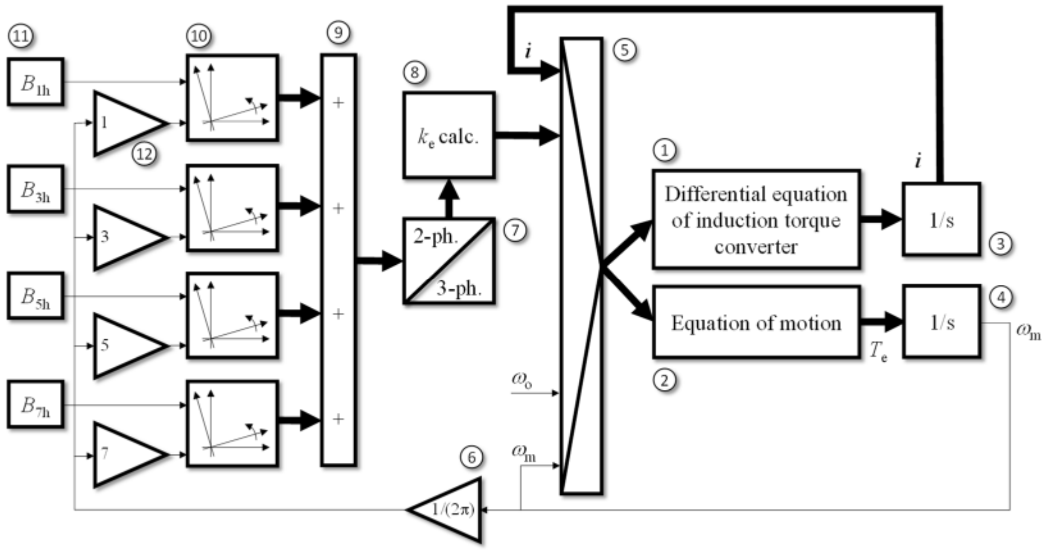
An important element in separating mechanically, but coupling electro-magnetically, the torsional vibration generator and the main drive motor, is the inductive torque converter. The induction torque converter is an electro-mechanical device which converts mechanical energy into mechanical energy, with the help of electro-magnetic fields excited by a set of permanent magnets. These interact with the electromagnetic field excited by the current induced (as a result of the permanent magnets' rotation) in the windings. The input mechanical energy is delivered from the driving motor, the generated motion is assumed as a rotating motion, and this generates a rotating electromagnetic field – the mechanical energy (of rotating masses) is transformed into the energy stored in rotating magnetic fields. These rotating magnetic fields excite the current flow in the windings of the induction torque converter, and finally excite the magnetic fields which interact with the rotating magnetic fields. This interaction forces the windings sets to move – the energy stored in the magnetic fields is transformed into mechanical energy (of windings motion) again.




*View of Cross-section of Induction Torque Converter of Torsional Generator*

The induction torque converter's task is to transfer the driving torque from the main drive motor without mechanical contact, but only through the magnetic field that couples the disc with the excitation circuit and the disc of the receiving element. It results in a significant reduction of vibrations by introducing magnetic field damping, which can be transferred from the generator to the drive motor. In addition, it is an element that protects the main drive motor against blocking in the event of blockage of the cutting head and torsional vibration generator. This is possible due to the lack of a rigid mechanical connection and the coupling of the excitation system and the receiving element by the magnetic field. The figure to the left shows the elements of the torque converter: the excitation system (1), the receiving element (2), the driven shaft (3), the output shaft (4), permanent magnets (5), and windings (6). The torque converter shown in the figure can be extended with additional disks, thanks to which it is possible to increase the values of transmitted powers and torques. This type of solution allows the converter to be scaled depending on the needs.

The mathematical model of the ITC was formulated in two steps. In Step 1 it was necessary to calculate the averaged values of the magnetic flux density in the air-gap. This result was used to calculate the so-called induced voltage and torque coefficient. In Step 2 the partial differential equation was formulated for winding of the receiving circuit. It was formulated as the



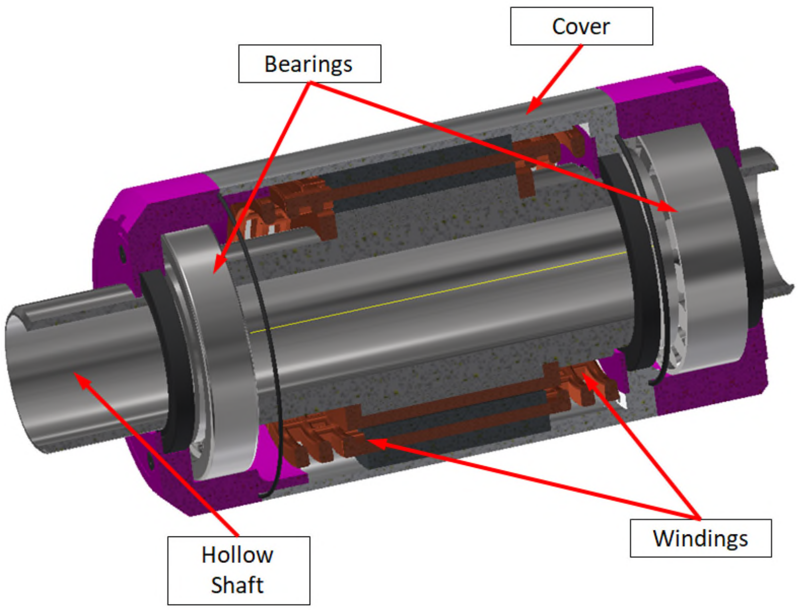

*Mathematical Model of Induction Torque Converter [2]*

so-called circuit model. The general schema for solving the induction torque converter differential equations is shown in the block diagram above. The right sides of equation are put into blocks 1 and 2 and are integrated in blocks 3 and 4. The results of the integration are given to the multiplexer at block 5 in a feedback loop. Block 8 calculates values of the $k_e$ coefficients, and the value of the angular speed $\omega_o$ of the excitation circuit also enter into the multiplexer at block 5. In block 11 the amplitudes of the magnetic flux density harmonics are set. In the amplifier at block 6 the rotating frequency is calculated and it is an input value to the amplifiers at block 12. Both these sets of quantities are necessary to calculate the time varying magnetic flux component in 2-axes coordinate systems in block 10, and thereby calculate 3-phase plots of the magnetic flux density components in block 7 using an inverse Clark-Park transformation.

## Main Driving Motor

The third element of the drilling rig is the main drive motor. This motor is designed using permanent magnets and can be classified as a permanent magnet synchronous motor – a kind of electromechanical transducer. In this kind of transducer – in the case of conversion of electrical energy into mechanical energy – electric motors, in which previously magnetized permanent magnets are used, have one uncontrolled source of the magnetic field, related to permanent magnets. The second source of the magnetic field is the winding supplied by electrical energy. The magnetic field generated by the winding can be either a direct field or a time-varying field, where the value of the magnetic field is determined by the parameters of the power supply. In the case of 3-phase AC motors (e.g. synchronous motors), the field generated by the winding is a rotating field with a rotational speed depending on the frequency of the supply source. The interaction of the magnetic field produced by the winding and the magnetic field produced by the magnets is the source of the electromechanical torque (mechanical energy) produced by the motor. This motor generates the necessary driving torque to rotate the cutting head in the desired direction and drive the screw conveyor. The motor windings are made in the same way as the torque generator windings, i.e. they have the same number of pole pairs, the number of phases and they occupy the same number of slots. This approach will significantly reduce the cost of prototyping in the future, as the stators and stator windings are the same in the torsional vibration generator and the main drive motor. The figure below shows the main components of the motor: stator windings (1), rotor shaft (2), permanent magnets (3), and bearings (4).

Taking into account the prepared drawings of all designed components of the drilling rig, as well as the formulated field and circuit mathematical models, it is reasonable to proceed to the next stage – building a prototype. In addition to building a prototype of a drilling rig, thanks to the mathematical models, it will also be possible to prepare a concept of the control systems for such a complex object as a new type of drilling rig.




*View of Cross-section of Driving Motor (Induction Motor)*

## References & Further Reading


Trawinski, T.; Szczygieł, M. and Tomas, A. (2019) *Electromagnetically Excited Torsional Vibration to Rock Drilling Support*, 2019 19th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, Aug. 2019, Nancy, France, pp. 29-31.

Trawinski, T.; Burlikowski, W.; Szczygieł M. *et al*, (2020) *Modelling of Drilling Rig with Electromagnetically Excited Torsional Vibration*, by Wydawnictwo Politechniki Śląskiej, ISBN 978-83-7880-730-8, No. 863, 2020, Gliwice, Poland.

# A Mesh-based Through-the-Earth Communication System

***David Gibson** and **Mike Bedford**, of the University of Exeter and **Angel Rodríguez** of Universidad Carlos III de Madrid describe the concept of a radio system, that will operate through the rock, thereby allowing rescue personnel to communicate if a mine's normal systems are inoperable.*

Two different methods of emergency communication have been developed in the INDIRES project to allow rescue teams to communicate when a mine's permanent systems have been compromised. One system uses a wire that is laid along the gallery by the rescuers as part of an incident response. This wire guides radio signals along the gallery, and in a way that is not affected by bends or obstructions, and allows rescue personnel to use handheld radios within a few metres of the wire. You read about this system in another article in this *Newsletter*.

The system described here does not need a guidewire, but it does require equipment to be permanently installed in the mine. Unlike a mine's normal wired communication systems, though, the equipment is generally capable of withstanding fires, explosions, falls of rock and other adverse events. This is because it transmits and receives signals through the rock so it does not rely on potentially vulnerable cables, and the equipment can be installed in a borehole in the gallery wall to provide additional protection. Such a system is intended for use between a rescue team and a rescue controller, between members of the rescue team, and between rescuers and any miners who have been affected by the incident.

It is also important to point out that the technology described here is also a constituent part of the resilient survivable sensor unit that is described elsewhere in this *Newsletter*.

## Through-the-Earth Radio

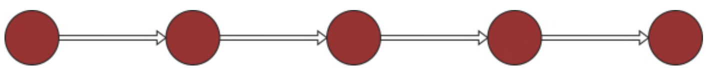
It is commonly thought that radio signals can't travel through rock but that's not really true. It is possible to transmit signals through rock to a degree, although coal-bearing geology is an especially difficult medium for communication. For this reason, through-the-earth (TTE) communication is only possible through coal and shales if a suitably low frequency is used. However, this often means that the equipment operates in the so-called "near field" that poses some significant challenges.

Near field signals reduce in strength very rapidly with distance. This can mean, for example, that to double the range it might be necessary to increase the power by a factor 64. Scaling this up, to quadruple the range, more than 4,000 times as much power would be needed. Needless to say, this power requirement escalates very rapidly with distance and soon reaches the point at which it is barely practical. Although TTE systems have been used in coal mines – for example in the USA and Australia – the equipment is extremely expensive, it uses very high levels of power, and it can usually transmit in one direction only, from the surface to underground. TTE radio has, therefore, previously been considered impractical for providing two-way rescue communication following a mining incident.

The system developed in INDIRES, however, overcomes the difficulties by operating as a mesh network. Instead of transmitting directly from one end of the communication path to the other, the system relies on repeater units, otherwise known as mesh nodes. This means that signals only have to be transmitted a short distance to the closest mesh node. When that node receives a signal, it re-transmits it to the next node and this continues until it reaches its final destination. Because of the short distances between nodes, high levels of power are not required, and operation using internal batteries is possible.

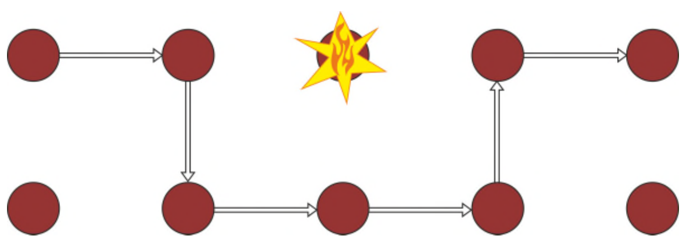
A mesh node also provides resilience to the failure of some nodes, which is important for rescue communication following an incident. So long as each node has some spare capacity, so it can increase its power if necessary, if one node is destroyed it can transmit its signal to the next available node. Alternatively, for some mesh arrangements, it might be possible to send messages via a completely different route without increasing the power. In the diagram below-right, for example, mesh nodes are installed in two parallel galleries and this allows use of an alternative route.

TTE mesh nodes work independently of the mine's wired power and communication networks but can also use these systems if they're available. In addition to internal batteries, therefore, they can operate from external power and, in addition to having a TTE capability, they can communicate via a wired network. Together, these options provide a greater degree of redundancy and immunity from faults.



*Under normal conditions, messages are sent via consecutive nodes from end to end.*

*If a node is destroyed, however, the other nodes have sufficient reserve power to bridge the gap.*



*Alternatively, it might be possible to route messages via nodes in an adjacent gallery without increasing the power.*


*The transceiver is based on the Teensy 3.5 computing module.*

## Mesh Node Prototype

As discussed later, the outcome of this part of the INDIRES project is considered a proof-of-concept, so interested parties are likely to be research organisations rather than end users. Accordingly, the coverage here is more technical in nature than in most of the articles in this *Newsletter*.

### Internal Electronics

The mesh node is designed around a small microcomputer module with ample memory and abundant I/O pins. In the current implementation, a Teensy 3.5 module (**www.pjrc.comstore/teensy35.html**) was selected, because the originally envisaged Arduino MKR did not have enough I/O pins. Moreover, it has three times the clock speed of the MKR, so processing power is significantly greater, making the software-defined radio (SDR) baseband processing simpler. To this basic processing module, the following elements were added:

1. an interface to a 3.5" QVGA graphics LCD, for displaying debug and test data,
2. radio interfaces – including analogue circuitry for interfacing with an external microphone and a loudspeaker or a headset - which allow great flexibility in the possible modes of operation, be they analogue or digital, data or voice,
3. a sensor interface, for direct connection of the SIB-02 sensor board, in anticipation of its use in the resilient sensor unit that is described in a separate article in this *Newsletter*,
4. a keyboard interface (used for tests),
5. power supply circuitry, with low standby power and selective disconnection capacity.

Although, as a proof of concept, the design it is not designed to be ATEX compliant, it was designed for an easy update to meet ATEX requirements.

The radio receiver (wireless interface) itself is a Zero-IF design based on a Quadrature (otherwise known as Tayloe) mixer. Its operational frequency can be anywhere from VLF to HF, to allow flexibility in the operating frequency. The radio transmitter allows for efficient operation in the expected operation frequencies, and it can be operated in both digital and analogue modes, for data and voice transmission.

### Data Routing Algorithm

Because INDIRES is a research project we decided to adopt a communications architecture that was optimised for development rather than for speed, so data packets would be processed as part of the so-called ‘application layer’ protocol, and would be routed with human-readable headers. But although a specific routing layer is not present in our system, routing is still a highly important feature, which we have implemented within the application layer. Each node has to know to which devices it can send packets, and what route to take to a given destination. There are three distinct stages to the operation, which we refer to as mapping, routing and linking.

Mapping is the process of determining the structure of the network and distributing the information to the individual nodes. A typical example of such an algorithm is Ad-hoc On-demand Distance Vector (AODV) routing in which a node broadcasts a ‘ping’ to all devices on the network. Those that receive it repeat the ping, and thus the mapping process continues. However, in our application, to avoid the problem of data clashes and consequent re-tries, we use a variation that is more like a tree-based search. The salient point is that because this operation is just an initial mapping exercise, speed is not important. Our network spends most of its time idle and so has plenty of spare time in which to execute a simple but slow algorithm. The information that is gathered by this exercise comprises the *network map*.

Once an originating node has built a network map it can apply a routing algorithm to the data, to construct a *routing table*. That provides the optimum, or lowest cost route between any two nodes. The resulting table is a matrix showing, for each possible pair of nodes, the one that is the initial point of contact along the route. Once the table has been determined, it is broadcast to all nodes. The traditional Dijkstra algorithm (which predates computer networks) is suitable for this task.

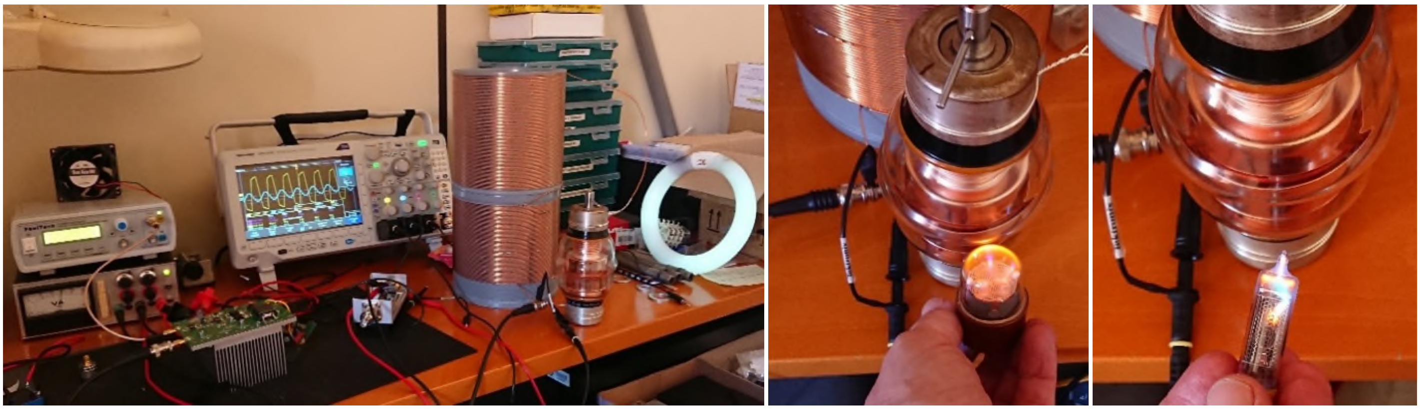
Linking is the notion of sending pre-routed data across the network. Instead of each node determining the next node by looking at the routing table, the originating node specifies a complete route in advance, and transmits that information along with the data payload. This is primarily a convenience during development but it does confer some advantages in a project such as this one.

### Antennas

One of the most obvious types of antenna for this type of near field communication system is a tuned loop. Significant effort has been put into building, simulating, and practically testing – both in the laboratory and in an underground environment – a selection of antennas of various sizes and characteristics. This has led to the establishment of a step-by-step antenna design procedure.

Although, for this project, we have undertaken practical tests using air-cored cylinders, we suggest that other antenna systems merit further study and have carried out extensive theoretical studies into several alternatives. It is though that the choice of antenna type could be one aspect of the TTE mesh node that would benefit from an analysis of the characteristics of the mine in which it is going to be used.

One attractive option would be to use an untuned loop antenna. Wideband untuned loops have seen success in sub-sea applications where video has been transmitted over short distances. The characteristics of an untuned loop mean that it can be designed to avoid skin, proximity and self-resonance effects in its winding so, in these respects, it is a more attractive option than the tuned antenna. Additionally, there are no design dilemmas concerning the number of turns to use, and we can use a single turn of wire or tape. With a tuned antenna, using a few turns of thick wire instead of a larger number of thinner turns can cause problems due to the low resistance of the winding, which



*Herte we see some of the laboratory tests being carried out on one of the prototype tuned loop antenna designs.*

then requires a very high current and can result in an inefficient power amplifier. But the impedance of an untuned antenna is largely governed by the inductance, not the resistance. It is true that there can be problems in driving an untuned antenna, but these are largely related to the use of an analogue power amplifier and do not apply to a digital system, although that is an added complexity to be dealt with. It is also interesting to note that if the limiting factor in the design of the antenna is the reactive voltage, then the performance when it is tuned (that is, the magnetic moment it produces for a specified power consumption) is identical to the performance when it is untuned. A node based on a small untuned loop might use under a watt of power and provide a range of 20–50m in a box about the size of a large paperback book. However, the R&D costs of implementing an un-tuned antenna design should not be under-estimated.

Another possible antenna uses a small ceramic tile. It was decided that, for pragmatic reasons, a more traditional antenna was better suited to this project although it might be worth further investigations. Such an antenna is expensive and requires specialised electronics but it does have some potential benefits – especially in a low-power repeater node. A ceramic tile might not be suitable as a magnetic field receiver but there is no reason why the *same* type of antenna *has* to be used for the transmitter *and* the receiver; and a ferrite rod is an example of this 'dual antenna' concept, with it being more suited for use in a receiver than a transmitter.

Lastly, grounded dipoles are known to be highly efficient, but they may run into problems with ATEX certification. As noted above, there is no 'one size fits all' solution and a particular application – whether for reasons of cost or geology – might require a substantially different antenna system.

## Enclosure

The enclosure for the TTE mesh node is a variant of the enclosure for the resilient survivable sensor which is described elsewhere in this *Newsletter*. This ruggedly designed enclosure offers a good degree of protection from environmental hazards that might exist immediately after an incident. It differs from the enclosure for the sensor unit, however, in that it does not require sealable vents to protect the internal electronics under extreme conditions, but which can open to allow the environment to be sensed.

## Path to ATEX Certification

As the prototype was intended as a proof of concept, the limiting components needed to implement a fully compliant intrinsically safe (Ex ia, M1) design were not implemented.

However, the path to implement intrinsic safety is quite straightforward. No special issues are expected. The power requirements of the current version of the design are not too high (less than 250mA at 12V), and therefore can be supplied from an intrinsically safe power supply or battery.

Moreover, the power supply design must be modified, adding fuses and limiting resistors for limiting currents and temperatures. Zener diodes will be needed to guarantee a limited voltage in the output of the regulators, in order to allow the amount of capacitance (hundreds of micro Farads) needed for the proper operation of the electronic circuits.

## Current Status

It was originally intended to produce a fully-working universal system that could be tested in a coal mine. However, as work progressed, it became clear that so many aspects of a system would be dependent on aspects of the mine including its size and layout and the geology. In particular, for optimal performance at minimal cost, it would be necessary to analyse the characteristics of the particular mine in order to select the type of antenna, the frequency of operation, the transmit power, the physical spacing of the nodes, and the network and routing algorithms. For this reason, a degree of flexibility was built into the electronic and software aspects of the TTE node prototype, as produced in this project. However, it was not possible to offer such flexibility is all aspects of the design, and while the current prototype allows the operating frequency and the routing algorithms to be altered, the type of antenna and the maximum transmitter power are fixed. This led to the inevitable conclusion that the field tests should be considered as a proof-of-concept, in the sense that they would only prove the correct operation of a TTE system in a particular mine.

In reality, the field testing of the system was not able to take place within the INDIRES project because of travel restrictions and other issues related to the Covid-19 pandemic. The current status of the TTE system, therefore, is that there is potential for interested parties to be involved in further research and testing, leading to a design that can be made available to the mines rescue community.

The current status, including full technical details of the prototype, is fully documented in a *User Documentation* for the TTE mesh system which is available on the project website at INDIRES.EU. This should provide sufficient information for research organisations who are potentially interested to assess the opportunity. The *User Documentation* also provides contact details if you would like to pursue this further.

# Unmanned Robotic Vehicles for Information Gathering

***Noé Pérez** and **Alberto Jardón** of Universidad Carlos III de Madrid outline the work that has been carried out in developing a team of robotic vehicles for checking a region impacted by an incident before deciding if it is safe to send human rescuers into that area.*

This part of the project has involved the development of several robotic vehicles that are able to work as a team. They are intended for rapid deployment to investigate areas of a mine that have been affected by an incident before committing personnel into potentially hazardous regions.

The team comprises a ground robot, a flying robot, otherwise called a drone, and a crawling robot. The concept of a team was conceived because it is likely, in most environments, that no single type of vehicle will meet all requirements.

The ground robot is a powerful tracked vehicle with a good operational time and payload capacity. However, despite its rough terrain capabilities, it is less suited to extremely harsh conditions than the other two robots. For these reasons, it has a two-fold function: as the ground robot as part of the team, and as the Vehicle Processing Hub, carrying the other two robots, plus the hardware for processing and communication, to the incident area.

The aerial vehicle is a low-cost medium-small sized quadcopter. It allows large areas to be covered in a short time. However, the operational time and the payload capacity are very limited.

Finally, the small crawler robot can cover only small areas of terrain, but it can access small cavities and holes. It is a six-legged robot, which can best be thought of as a spider-like vehicle.

## Ground Robot

The base commercial platform employed in INDIRES is the Raposa robot which is produced by the Portuguese Company IDMind (www.idmind.pt). This is a tracked robot with a differential drive, that was designed to operate in environments which are hostile to humans and for search and rescue operations.

Internally, the robot has a control computer and a low-cost IMU sensor. The motors also have encoder sensors that allow them to compute an odometry reading which is fused with the data from the IMU sensor. However, the work within the INDIRES project has involved adding autonomous exploration and navigation features, for which the following sensors and devices have been added.

First, a second computer (Intel NUC i7) has been added for distributing the processing burden of the sensors and the exploration and navigation algorithms between the two computers. The environmental sensors are connected to this computer.

Inside the front flipper part, a VDSL2 modem and a Wi-Fi router are mounted. The VDSL2 modem is employed for wired communication with the control station. The Wi-Fi router is used for communication between the two computers and the other robots in the team. Moreover, in the front flipper, two illumination LEDs have been installed.

For mapping and exploration, and navigation, two Intel RealSense D435 cameras with depth perception are employed. One of them also includes an internal IMU sensor. The point clouds describing the scene are obtained from these cameras, and employed to build the online map, and analyse the environment for navigation and exploration.

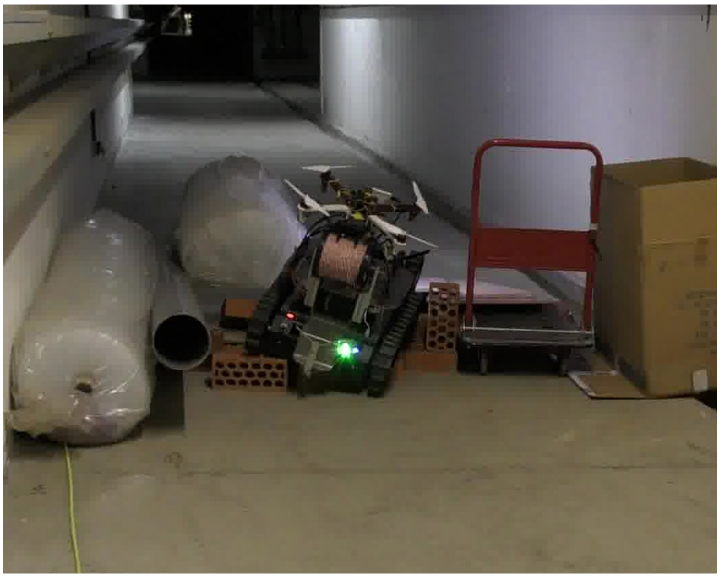
Finally, for obstacle detection, in the back and at both sides of the robot, a TeraRanger Multiflex sensor from the company Terabee is used. It comprises a chain of eight small time-of-flight sensors. The range of this sensor is 2m and it is intended for detecting close obstacles and avoiding collisions.

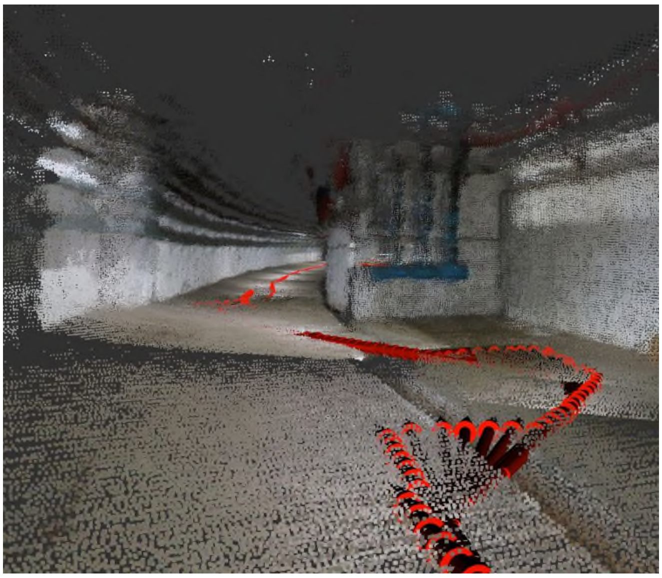
## Flying Robot

The base vehicle chosen is a low-cost quadcopter from the Spanish company ErleRobotics. Unfortunately, after the decision was made to use this product and the robot was obtained, the company underwent a merger and, as a result, this drone is no longer commercially available. However, its general characteristics and open source foundation ensure that it is still suitable for the INDIRES requirements.

The brain of the quadcopter is the ErleBrain 3. Its purpose is to provide the electronics and interfaces for sensors and devices that are required to achieve the necessary autonomy. ErleBrain 3 combines a Raspberry Pi 3 computer connected to a

*The robotic team comprises a tracked ground robot, a flying robot, and a spider-like crawling robot. The robots are not shown to scale.*





*Left: Ground robot negotiating obstacles. Right: Section of map captured by the ground robot.*

board which is an adapted and simplified version of a PixHawk flight controller. Pixhawk is independent open-hardware that aims to provide the standard for readily-available, high-quality and low-cost autopilot hardware designs for the academic, and developer communities. ErleBrain includes the following onboard sensors that are used to manage the drone: a 3-axis gyroscope, a 3-axis digital compass, a 3-axis accelerometer, a barometer, a temperature sensor, and an 8 megapixel camera.

The quadcopter needs additional sensors and devices to achieve autonomous operation. These are as follows.

Two Maxbotix MB1242 sonars. These have an approximate range of 6m, and a dowel diameter of 88.9mm. One looks down to measure the height of the drone, the other looks up to measure the distance to the ceiling.

A Teraranger Tower Evo ring of infrared ToF sensors. This lightweight unit includes eight sensors with a range from 0.4m to 60m. The field of view is approximately 2° per sensor, and 45° between each sensor axis. This device is used to detect the distance to any obstacles and so avoid possible collisions.

A Teraranger Evo Thermal 33 Thermal camera has been included to detect heat sources like human bodies for use in incident situations involving miners. The field of view is 33° and the maximum distance to detect the temperature of a human body is around 13m.

Finally, we have included a Teraranger 3D cam which is a ToF Depth camera. This is used to generate a point cloud which is employed in mapping and navigation tasks.

## Crawling Robot

The platform chosen is the 6-legged HEXA robot from the company Vincross. It is a multi-functional all terrain robot which is biologically inspired by spiders, and presents an agile and compact design. It can walk and climb, while taking photos and videos.

The onboard sensors that are included in the robot are a 720p camera, a 3-axis accelerometer, a distance measuring sensor, and an infra-red transmitter.

## Control

The operators of the team of rescue robots, situated in the control station, have two main requirements. First they need to receive online the information that the robots are capturing. This includes scene images, thermal images, data on environmental conditions, etc. Second, they need to be able to control – at a high level – the actions that the robots should perform. In order to achieve this, software has been developed to visualize the information and control the actions of the robots.

The high-level architecture of the navigation and exploration system is called the Exploration Manager. It represents the top-level decision-making component and it is in charge of implementing navigation functions through the concept of macro actions. The following macro actions are available.

Navigation – this action initiates the autonomous navigation of the vehicle to a local goal or location that must be provided by the user. This location must be inside the current or available known area for the ground robot, or approximately 10 meters around the aerial vehicle. The action ends when the goal is reached.

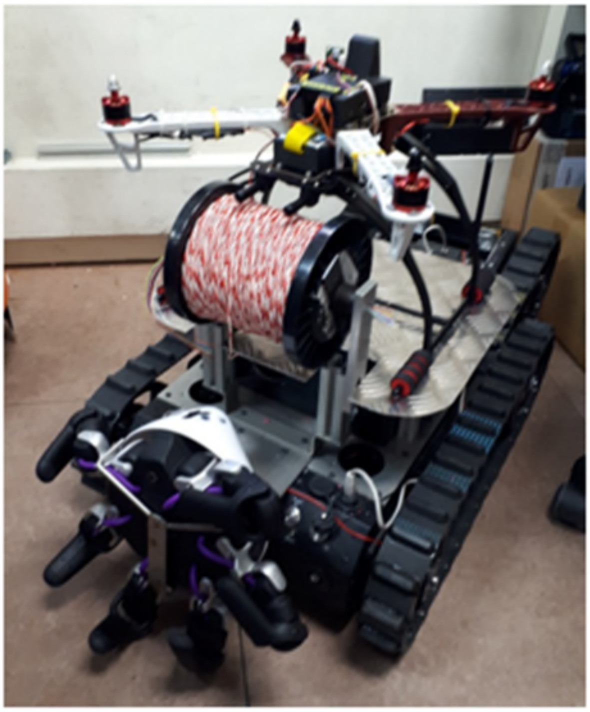
Exploration – this starts the autonomous exploration of the area with the aim of building a map of the area. It applies only to the ground vehicle. This action does not conclude until it is cancelled by the user, a new action has been triggered or the robot is blocked.

Teleoperation – this action, which is only available for the ground robot, allows the robot to be remotely controlled by the user, cancelling any current action. In case of the aerial vehicle, the teleoperation action is split into more specific sub actions such as changing the current altitude or change the current heading.

Go back home – because the manual control of an aerial vehicle is more complex than the manual control of a ground robot, we do not allow the manual control of the drone. Instead, we provide this action in which the drone will try to go back to its home position on top of the ground robot if possible. If the operation is too complex, the drone will land in an approximate position.

## Field Tests

Field testing of the robotic team had been scheduled to take place in an underground coal mine but this was not possible to due to the Covid-19 pandemic. For this reason, a set of underground service galleries at the UC3M Campus in Leganés were used. The width varies from 3 to 7 meters so they are not too dissimilar to mine galleries in their dimensions. Ramps and steps were available and various obstacles and restrictions were introduced to make the path deliberately uneven and to restrict access to some of



*The tracked ground vehicle also acts as the Vehicle Processing Hub, carrying both the drone and the crawling robot to the place of the incident for deployment.*

the robots. Nevertheless, the environment was not as harsh as that of a true mine.

Here, the conclusions from those field trials are provided, with some comments on problems encountered and suggestions for improvements that were identified.

In the case of the ground robot, the novel navigation and exploration system that had been developed was successfully demonstrated. Some problems were detected, such as that caused by vibrations that impeded the use of an IPS device for localization. Also, it was found that the use of only one RGBD camera for mapping and navigation presented a very limited field of view. Even with this limited view, though, the results obtained were promising, although we think that a multi-camera system with at least three cameras (one in the front and two in the sides) could improve, significantly the performance of the system.

We were not able to perform a thorough evaluation of the autonomous capabilities of the aerial vehicle and concentrated, therefore, on the tele-operation mode. However, the preliminary results and the simulations performed suggested an encouraging future for the application of this kind of vehicle in such environments.

Interesting conclusions were drawn from the use of the spider-like robot. It achieved very good performance in specific situations, like progressing through pipes or tubes, or through small holes in flat surfaces. However, it had problems in very rough terrain and its climbing capacity is not ideal because its sensory input is very limited.

In this project we have tried to progress in this research area applied to problem of underground mines. In such a complex environment, all the locomotion styles and robotic approaches present different advantages and disadvantages. Therefore, the idea of using a team of vehicles with different capabilities seems to have been justified.

## Current Status

It is clear that the basic operation of the robots, including the use of sensor information to generate a map of the environment and to use that map for navigation purposes, has been successfully demonstrated. The operation of different types of robots, working together as a team, has also been demonstrated. Furthermore, although the test environment was different to a real mine in many respects, it is expected that this key functionality will apply to the mine environment, perhaps with some further adaptation as found necessary. Since much of this functionality was not previously available, it is encouraging that the significant amount of research work that has been expended in developing these technologies has reaped benefits.

However, it is also evident that the mine environment is very different from the environment used for these tests and it has not been possible to demonstrate the ability of these robots to withstand the harshest environmental conditions. From the information that has been provided, it would appear that the robotic vehicles would not be adequately protected for use in some post-incident environments. In particular, it is thought that the tracked ground robot would probably be most affected by unfavourable conditions. It is envisaged, for example, that in some cases, the nature of the terrain and the condition of the tunnels after some collapse, rock burst, fire or explosion, might render the drone as the most suitable or even only usable vehicle for use in rescue operations. Although these comments might seem negative, they should be read in the light of the fact that it has not been possible to prove how effective the robots would be in a post-incident mine environment and are, therefore, the result of an attempt at analysing the limited information available.

Given that it is likely that the robotic vehicles are not entirely suitable in their current form, it is appropriate to consider the current status of the development work and the potential for further development after the end of the INDIRES project. Reviewing the work that has been carried out, it appears that the major part of the research and development was into the techniques required for mapping and navigation and the provision of an autonomous capability. It seems that this emphasis was required because these were unsolved problems in an unstructured environment such as a mine following an incident.

To allow maximum time for this software development work, the hardware platforms used to demonstrate these developments were based on commercially available vehicles, modified as necessary. These vehicles were chosen taking into account their ruggedness – for example, the tracked robot was designed to operate in environments which are hostile to humans and for search and rescue operations. Even so, given that the mine environment can be classified as extreme, is likely that it would be necessary to find or design alternative robotic hardware onto which the novel technologies developed in INDIRES could be ported. This would be necessary for the robots to be considered useful for universal deployment following a mining incident, instead of being suitable only in some cases.

Also, the equipment is currently not ATEX certified. Further development work is needed, therefore, to address this issue.

To summarise, therefore, there is potential for further development after the completion of the INDIRES project, building on the extensive development already carried out and demonstrated in a tunnel-type environment. UC3M are open to future collaboration within the framework of new projects, in order to achieve the desired usefulness and solve the aforementioned ATEX requirement. In addition, project partner Premogovnik Velenje would welcome any such follow-on work including the opportunity to trial the results of any such developments in the coal mine that they operate.

# A Resilient Survivable Environmental Sensor

*A mine's normal environmental sensors, and the power and communication networks on which they depend, are at risk during an accident so a resilient alternative has been designed. **Mike Bedford** of the University of Exeter and **Angel Rodríguez** of Universidad Carlos III de Madrid outline the concept and the design, and proceed to discuss the ongoing development opportunities.*

The sensors which monitor a mine's environmental conditions during normal operation are liable to failure during a serious incident such as a fire, explosion, fall of rock or flood. This could be because the sensor itself is damaged or because of damage to the mine's permanent power and data networks which are used by these sensors. Yet information on the conditions in a mine is essential in planning a rescue response to an incident. For example, this type of data could inform a decision on whether it is safe to dispatch rescue staff into a region of the mine that has been affected by a fire or explosion. In addition, although such information isn't usually provided by normal operational sensors, being able to detect the presence of miners in particular areas of a mine could be highly beneficial in rescue planning. With this in mind, a programme of work has been undertaken in the INDIRES project to design the concept for a sensor unit which is sufficiently resilient that it is able to survive the adverse conditions immediately following a serious accident and so provide essential information to mine management and rescue controllers.

## Concept Overview

Ordinary sensor units are at risk because they are installed on the wall of a gallery where they are subject to damage by a blast wave travelling along the gallery from an explosion, or from falling rock or other objects. They are also at risk from high temperatures and flood water. To prevent damage from these occurrences, the concept of the resilient survivable sensor requires that it should be installed in such a way that it is protected from blast waves and high velocity debris carried by the pressure wave. This process is described in more detail in the section titled "Installation". The design also requires it to be sealed under normal conditions – to protect it from any high temperatures or water – with the ability for the seals to open when the conditions become less severe so the internal sensor elements are exposed to the atmosphere and the unit is, therefore, able to monitor the environment.

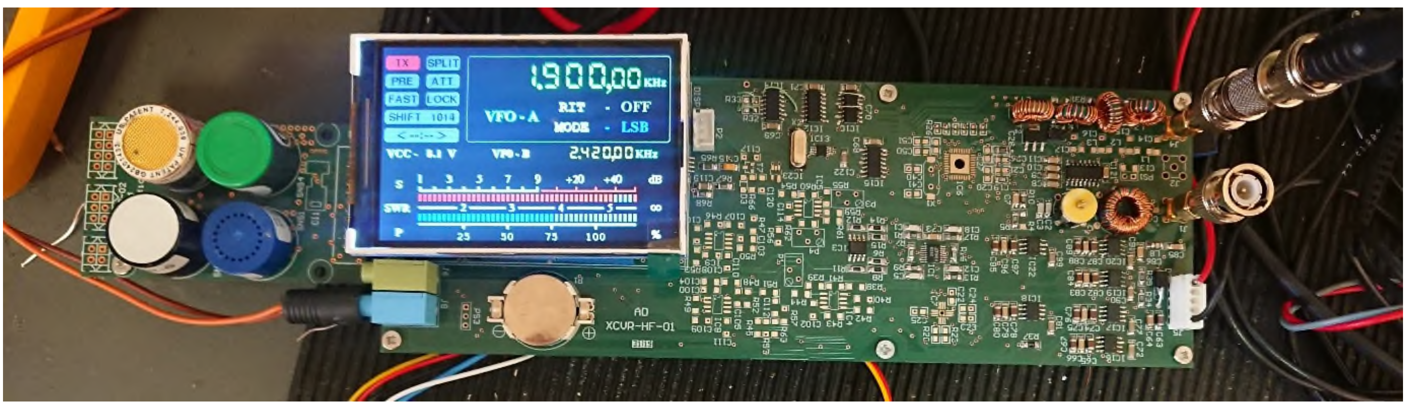
In addition to the risk to the sensors themselves, standard sensor units are vulnerable because the wiring to the mine's power and data networks is also surface-mounted on the wall of roof of the gallery. As such, this wiring is liable to severe damage from a whole range of issues including fires and explosions. Unlike the actual sensor unit, it is not feasible to install the wiring into recesses because this would be a far too expensive option. For this reason, the design concept was for the sensor to operate via the wired network whenever possible, but in the event of failure of that network, it could operate wirelessly. Two approaches were introduced to allow operation that does not require access to fixed networks.

First, the sensor was designed with internal batteries that would be capable of providing power if the wired power network becomes unavailable. Although the prototype uses rechargeable batteries which can be continually charged via the wired power network, there is provision to swap these for non-rechargeable batteries that will be able to offer a longer shelf life of at least 10 years to minimise the requirement for frequent maintenance. Facilities have also been provided to allow regular checks on the batteries and other hardware to be carried out remotely.

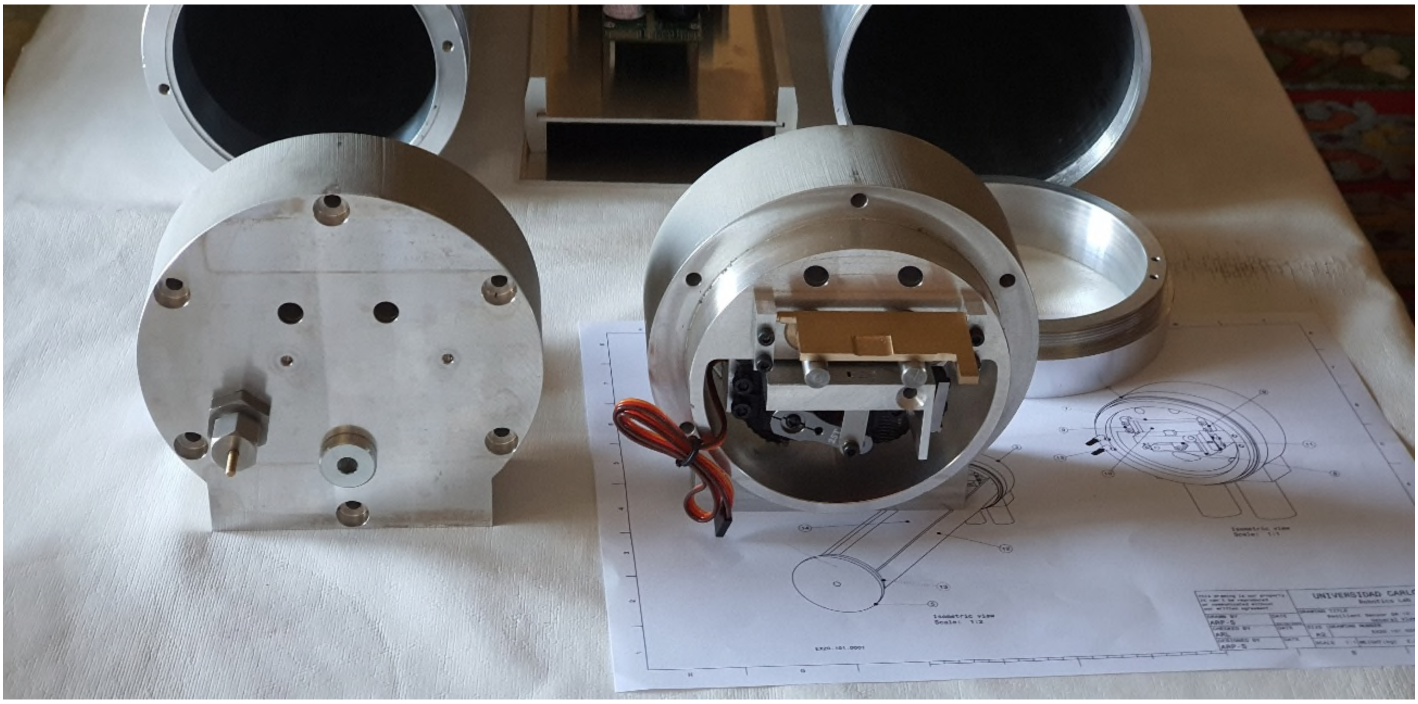
Second, in addition to a wired communication capability, the sensor unit is designed so that it is capable of communicating wirelessly. Specifically, it operates via through the earth (TTE) radio so that it is unaffected by local tunnel conditions or even by rock falls. To achieve this, the sensor units are designed to operate as parts of a network of low frequency TTE mesh nodes, a concept that you can read about in a separate article in this *Newsletter*.

## Electronic Design

The electronics of the resilient sensor is largely based on the mesh node prototype which is described in a bit more detail in the separate article in this




*Here we can see the main electronics board (with an LCD Screen for diagnostics) and the sensor interface board.*



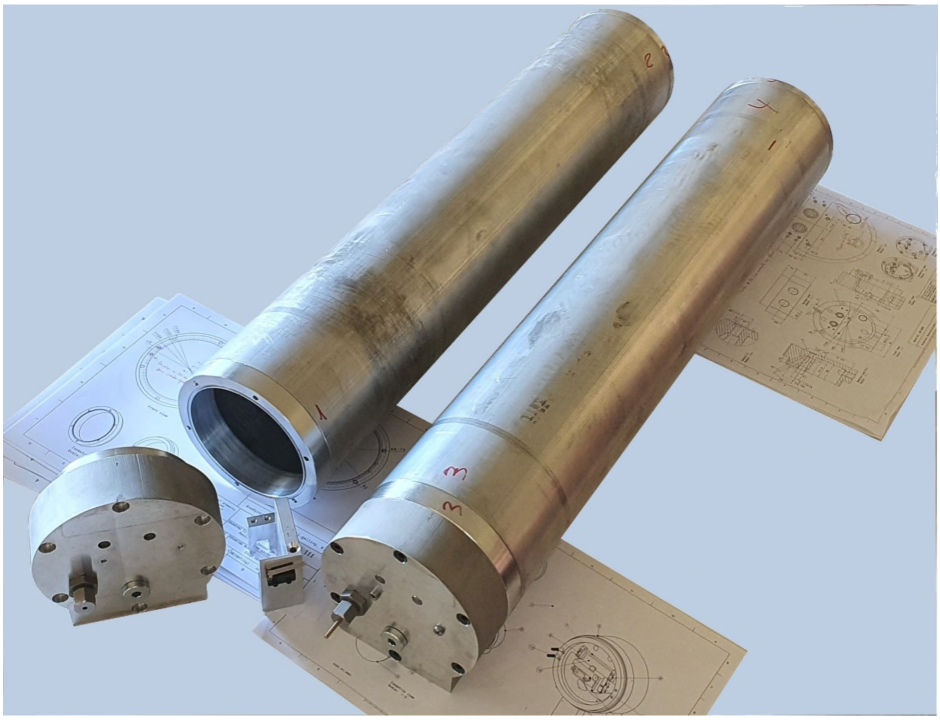
*In this view of the prototype enclosure, the seals are open, thereby allowing environmental sensing to take place.*

*Newsletter* on the TTE (through-the-earth) communication system. When designing the mesh node electronics, it was envisaged that it would fulfil a dual role, both as a mesh node and as the core for the resilient environmental sensor. To allow all the necessary sensors to be connected, an interface was included in the design and a complementary sensor board, with a mating connector, was designed to provide sensor support. The main electronics board with the sensor board attached is shown at the bottom of the previous page.

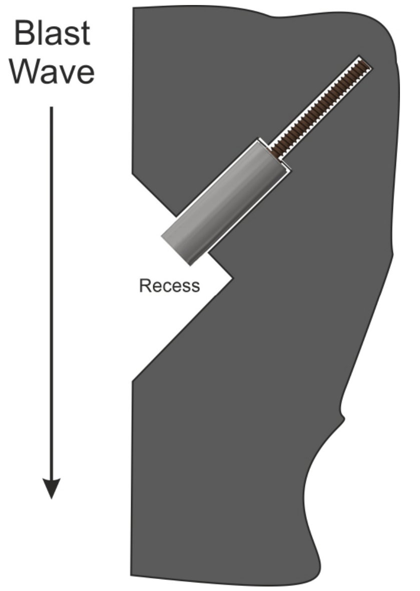
## Mechanical Design

The following are the main features of the mechanical design:

1. The external diameter is 130mm, allowing the use of 134mm drill bits for drilling the installation borehole.
2. The enclosure proper is composed of a front cover, an adapter ring (flange), a cylindrical body and a rear cover. Unions between them are flameproof. Also, O-rings are fitted for water-tightness.
3. It can be opened from the front by removing six hex socket (Allen) bolts. This allows easy inspection, servicing and resetting of the device. When the front cover (carrying the glands for antenna and power / data cables) is removed, the mounting plate (or tray) can slide out, allowing access to the electronics and batteries.
4. The body is 600mm long, much longer than needed for housing the electronics and gas sensors. This allows the installation of seismic sensors on the rear cover, if needed. The rear cover is solid, and 25mm thick, so blind holes can be drilled without losing water and flame-proofness. Also, a rebar can be attached to the rear part, through a threaded blind hole.
5. It was considered unnecessary to add fire shielding. Rock will shield the sides and back, and, if needed, insulation material can be placed on the front cover.
6. The enclosure – and by extension, the fixed sensor – has two states: closed when sleeping and open when alive.
7. When closed it is watertight and flameproof (in the ATEX sense, protection mode Ex d).
8. When open, all operating circuitry is intrinsically safe (Ex i).
9. It has pressure and temperature sensors to allow the external conditions to be checked before opening.
10. When open, two 8mm sampling vents allow the ingress of external atmosphere for analysis by the



*Prototypes of the resilient survivable environmental sensor.*




*Mounting configuration (top view).*

internal gas sensors and to “hear” external noise with a microphone. This latter facility offers a means of detecting nearby miners.

11. The vents are normally obturated by plungers. These plungers are spring-loaded and will open only when a locking plate is released. But, when closed, they are designed to make a flameproof joint with the cover. Moreover, they have O-rings for water-tightness.
12. The actuator for opening it is a high-torque servo, moving the retaining catch that holds the locking plate. A limit switch is fitted and wired to interrupt power to it when the retaining catch releases the locking plate (and plungers). At this point, the enclosure is still flameproof (Ex d).
13. Resetting (rearming, closing plungers and repositioning the locking plate and retaining catch) is done manually, as it will require an inspection of the device.
14. The enclosure is designed for a minimum of 25 bar overpressure, both internal and external.

## Prototype

Following the detailed mechanical design exercise, an order was placed with a third-party manufacturing company for a prototype of the enclosure. However, the prototype enclosure, as received, was not fully complete because of Covid-related staffing issues.

Some remedial work was carried out in-house. The work of fitting the electronic components into the enclosure was subsequently carried out but it’s important to recognise that, because of the manufacturing difficulties, the current prototype is not sufficiently complete to allow in-mine testing. The two photographs on the previous page show the prototypes.

## Installation

The sensor is designed to be securely mounted in a borehole in the gallery wall and fixed with grout to provide maximum protection from pressure waves and debris carried by a blast. To improve the fixing, there is the provision to add a length of rebar to the rear of the unit. However, because the end of the sensor unit where the sensing elements are mounted must be exposed to the atmosphere, a small portion of the sensor unit must protrude from the borehole. To provide protection for this exposed part of the sensor, therefore, the hole is drilled in a recess which will provide the necessary protection. This recess may be either prismatic or rectangular in shape, and the orientation can vary, the decision being made on local conditions. It is strongly recommended that it is mounted in the wall of the gallery, not the roof, to keep it away from any accumulation of hot gasses. The diagram above-left shows a possible mounting configuration.

Accordingly, installation involves the following processes. (1) Removing a steel arch support (only needed in mines with steel arches, and where those arches are too closely spaced to allow the niche to be excavated), (2) excavating a niche in the gallery wall, (3) drilling a hole in the niche, (4) wiring the sensor unit to fixed power and communication networks, (5) injecting resinous grout into the hole, and (6) inserting the sensor unit into the hole and supporting it until the resin has cured. More detailed instructions – which were formulated in conjunction with the mine operators in the project consortium – are provided in the *User Documentation* for the sensor unit.

## Path to ATEX Certification

A strand of possible future improvements is oriented to achieving ATEX compliance. Some discussion of this appears in the separate article on the TTE communication system and is relevant to the resilient survivable sensor unit because if shares the main electronics board. Here, though, some reference is made to those aspects that relate specifically to the sensor unit.

The approach used in the design of the fixed resilient sensor called for a dual protection mode: when armed, the enclosure is flameproof (Ex d), while it is intrinsically safe (Ex ia) when deployed. This aspect was implemented in full when designing the enclosure.

However, the need to use a non-intrinsically safe actuator to deploy the sensor reliably was recognized. Therefore, power to this actuator is removed as soon as it completes its function of releasing the locking plate, by means of a limit switch located appropriately. Moreover, it may be convenient that the external sacrificial sensors be not intrinsically safe. They are useful only until the unit is deployed, and only their mechanical parts are protruding, as the electronic parts are fully enclosed in the sensor enclosure. In this case, they shall be de-energized, too, when the sensor is deployed, because they are not needed anymore. The same limit switch can be used for this purpose.

As the prototype was intended as a proof of concept, the limiting components needed to implement a fully compliant intrinsically safe (Ex ia, M1) design were not implemented.

These modifications could be made as part of an exploitation strategy, perhaps in conjunction with other interested parties.

## Current Status

Prototyping and field testing of the prototype sensor were both negatively impacted by the Covid-19 pandemic. In particular, lockdown measures meant that the manufacturing of the prototype was severely delayed and the unit that was eventually received was incomplete. This, together with the travel restrictions that affected most project partners, resulted in the underground tests being cancelled.

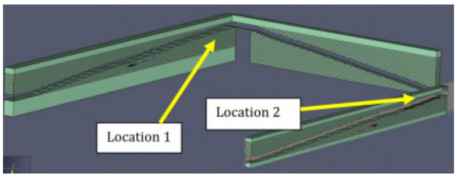
The current status, therefore, is that the resilient survivable sensor is at an advanced stage of development, but the prototype requires some further work before field testing can be carried out. There is, therefore, the opportunity for third-party collaboration to bring this element of the project to the point at which it is ready for large-scale trialling by a mining company and/or volume manufacture. More complete details of the resilient survivable sensor have been provided in the *User Documentation*. This comprehensive document can be downloaded from the project website at INDIRES.EU. The INDIRES consortium would welcome any expressions of interest with a view to making this key part of the project available to the mining community. The *User Documentation* gives details of who to contact should you be interested in this opportunity.

# Environmental and Evacuation Simulation During a Mine Emergency

*Daniel Octavio de Toledo and Rafael Sánchez of Geocontrol explain why it is important to include both CFD and evacuation simulations when it comes to making safety assessments during the response to a mining incident.*

All other aspects of the INDIRES project have concerned the acquisition of live data to assist in planning a rescue operation. However, it has to be recognised that sufficient real world data cannot always be made available. For example, although one element of the INDIRES project has involved the development of resilient survivable sensors, it will never be practical to install these in all areas of a mine.

To provide an alternative source of information to mine operators and rescue coordinators following an incident when the necessary live data isn't available, two simulation tools have been developed. As well as providing a resource for rescue planning, these tools are also essential in forward planning exercises. For example, they can be used to verify whether, in case of an emergency, a mine is adequately equipped to prevent and mitigate a fire, and whether the miners can get to a safe zone in a timely manner following an incident.




*The exact location of a fire can have a profound effect on the direction of movement of smoke.*

The work that has been done in this phase of the project has focused on two aspects. First, a CFD (computational fluid dynamics) method for simulating the environmental conditions in the case of a fire – for example, temperatures and visibility – has been produced. Second, a simulation approach has been developed to allow escape routes to be analysed. During an incident, this technique will allow the most likely evacuation routes taken by miners in the case of a fire to be determined.

The two simulation approaches can also work together. For example, the CFD fire simulation tool combined with the evacuation simulation tool allows an assessment to be made regarding whether the mine fulfils the necessary safety requirements and has the means to put in place a procedure that protects its workers.

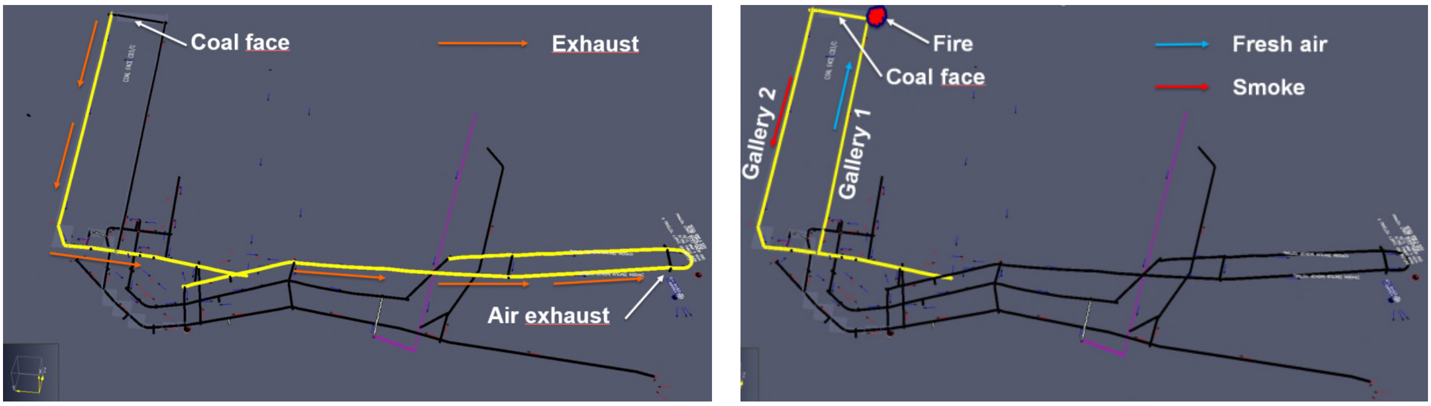
## CFD Fire Simulation

A fire simulation can be defined by a number of features, such as the type of burning material, the location of the fire, the geometrical arrangement of the mine, etc. In order to better characterise a fire in this infrastructure, some data and statistics have been obtained from public websites and governmental entities, like NIOSH.

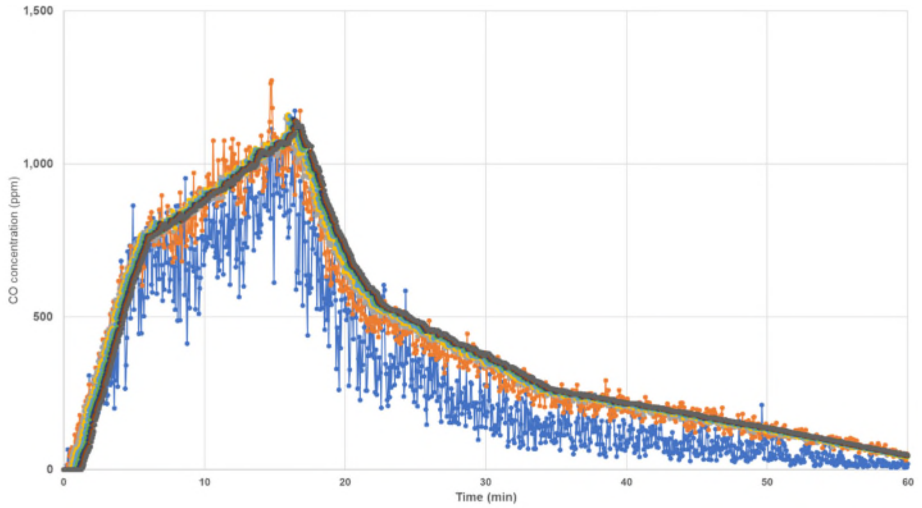
This data identifies which materials are more likely to ignite in a coal mine fire. For example, statistics suggest that the majority of fires in are caused by electrical issues, flame cutting, spontaneous combustion and conveyor belt friction.

In the lack of definitive information during the early stages of an incident response, this guidance may be used for modelling a fire in a mine. This way it provides a starting point about the features of a likely fire, namely the chemical reaction involved in the combustion, the heat release rate (HRR) curve, and other aspects including the surface where the fire occurs.

The fire location is another very relevant parameter when we consider that a mine constitutes a large network of interconnected galleries, possibly with different slopes. Because of buoyancy forces, the smoke has the tendency to advance towards the upward slopes and, therefore, depending on the fire location, the path taken by the smoke can totally differ from one place to another. For pre-emergency planning purposes, when the safety of a mine is evaluated, it is common practice to choose the most unfavourable locations, because this will give more solid assessments.




*Simulation can lead inform decisions on changing the line's normal exploitation ventilation (left) to one designed to better handle conditions during a fire (right).*




*An important output from a CFD simulation is the concentration of various gases. Here we see how the CO concentration downstream of a fire evolves over a period of one hour.*

Additionally, the exploitation conditions in the mine at the time of the breakout of the fire are other important factors to consider because they might influence the evolution of the fire.

On the one hand, poor ventilation conditions lead to a higher probability of fire because coal ignition often takes place under poor ventilation. However, on the other hand, good ventilation can result in a higher production rate of carbon monoxide (CO), thereby leading to conditions that are more hazardous. Conversely, good ventilation conditions favour toxicity dilution, but also contribute to the spread of the smoke to more regions of the mine, putting more people at risk.

In all cases, however, the exploitation ventilation has a major impact when a fire occurs since it has a major impact on the direction of movement of the smoke, especially in the early stages. This, therefore, influences the affected regions.

A CFD fire study is especially powerful in allowing a sensitivity analysis to be carried out. By varying the ventilation rate, it is possible to determine the most favourable and unfavourable fire scenarios.

Considering the emergency procedure is the final step in simulating a fire. This procedure usually establishes the ventilation regime that will be imposed once a fire is declared. The strategy in many cases consists of maintaining the initial sense of the ventilation during the exploitation phase.

Once the simulation is concluded, it is possible to analyse the spread of the smoke and the evolution of all the variables related to it, for example temperature, CO concentration and visibility.

## Evacuation Simulation

Evacuation simulation allows a determination to be made about whether those miners affected by an incident can reach a safe zone before the conditions in the mine become lethal or harmful.

In order to have solid conclusions, several scenarios can be simulated, so that the mine's safety is put under scrutiny in a variety of conditions, which can be implemented thanks to the variety of CFD scenarios that will already have been simulated.

The evacuation model has to be integrated with the CFD simulation, since, this way, it is possible to determine the effects of the smoke on the miners who are trying to escape from the fire. For this reason, before launching the CFD fire simulations, it is necessary to know which evacuation scenarios will be studied afterwards.

The speed at which miners are able to evacuation the mine galleries depends on several aspects, all of which need to be taken into account. Included here are the presence of obstacles, the presence of smoke, and even the age and physical state of the miners. All these factors have to be considered when preparing an evacuation model, so that the results will represent the current situation in the mine.

A degree of forward planning is necessary here. In order to correctly put in place the obstacles in the galleries, it is essential that the staff who will carry out the simulation exercises have the necessary detailed information on the location and dimensions of equipment and, ideally, have visited the regions to be simulated.

Another important aspect is determining the escape route that miners will choose to reach a safe zone. Commonly a fire will block the preferred routes and, therefore, miners will try to get as far from the fire as possible. Simulation also allows the rescue brigade to choose a route to the location of the fire, depending on the path taken by the smoke.

The integration of further CFD fire simulation results is the final step in making an assessment on the safety of the miners, since it provides the necessary information about how long miners have been subjected to harsh conditions during their evacuation.

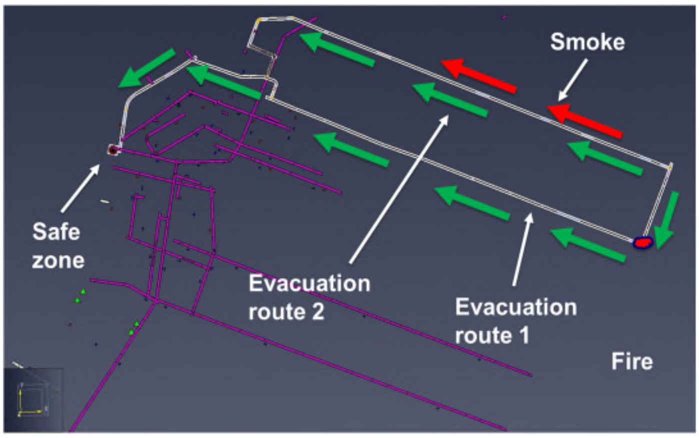
## Current Status

The information provided in the *User Documentation* for the two simulation tools is sufficient to allow end users to employ the techniques developed in INDIRES. Included here is full information on where to obtain the necessary software and how to use it. This guidance is both in general, and in the specific case of its use in simulation the environmental conditions and escape routes in mines. However, for parties who are interested in further developing these techniques, we make the following suggestions of areas for continuing research. Both rescue teams and mine operators could benefit from such follow-up work.

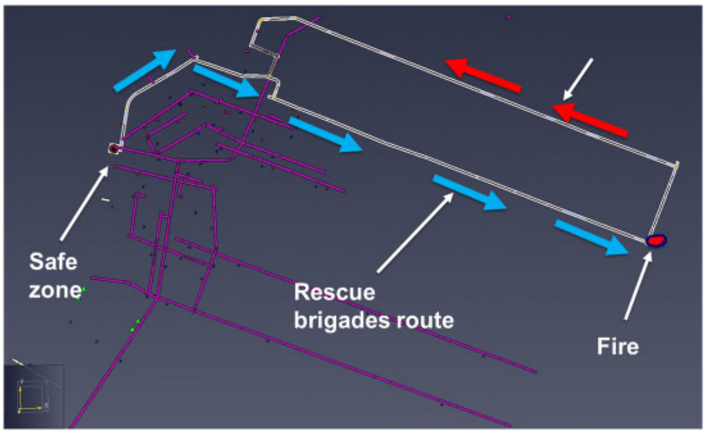
### CFD Fire Simulations

For mine operators conducting a safety appraisal, smoke behaviour during a fire is a key aspect to consider. In order to predict the path of the smoke, the first step is to build a model in the FDS software of the region where the fire occurs. Then it is necessary to verify if the path is the one expected after carrying out a fire simulation. For this purpose, it is possible to use a cold smoke generator to represent a small fire.

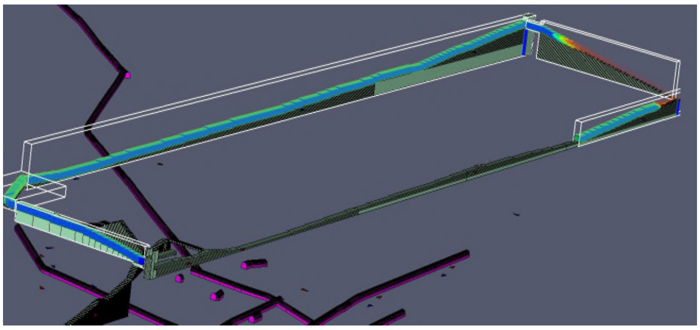
In addition, the activation of an emergency procedure should be considered. Temperature, visibility and CO sensors are key elements in detecting an incipient a fire. Our work considered just the type of sensors required, but further research can be done. Rescue teams can benefit from this element of work, since it allows a plan to be elaborated, integrating the sensors and describing which paths have to be chosen during an emergency intervention in order to avoid smoke.



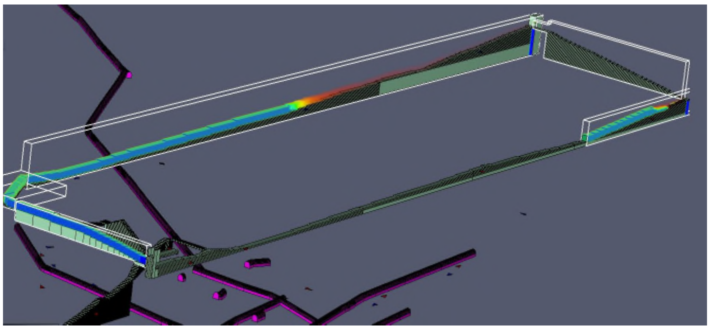

*Here we can see the escape routes in a mine after a fire is has been recognised.*




*The intervention routes in the mine during a fire will probably be different to the escape routes.*



*This display shows the visibility evolution in the mine during a fire after 120 seconds.*



*This display shows the visibility evolution in the mine during a fire after 360 seconds.*

Further work would be beneficial, since the first draft of a plan is mostly theoretical. To improve the performance of the intervention plan, it is necessary to consider aspects, such as the existence of obstacles, the interaction with miners already evacuating and the eventual lack of prediction of the path of the smoke. After several emergency exercises and a strict monitoring of the most important aspects of the intervention, new versions of this plan can be drawn up thanks to the feedback from these exercises.

Mine operators can benefit alongside rescue teams in the further definition of the optimal location of fire sensors. It is important to correctly choose the location, which can be done through some non-destructive tests, for example, a fire can be simulated with cold smoke, allowing visibility sensors to be tested. Our partners at the Velenje coal mine would welcome the opportunity to conduct these tests.

Ventilation manoeuvres in a mine, can be further analysed in collaboration with the Velenje coal mine. Included here are procedures for setting up the correlations inherent in each mine. Mine operators alongside rescue teams can benefit from cold smoke behaviour tests since this can be taken as a correlation for the emergency intervention plan.

## Evacuation Simulations

An approach for evacuation simulations covering the whole escape route has been developed in detail using the Pathfinder evacuation software. However, each mine and different regions of the same mine have their own features so further work needs could benefit mine operators.

By comparing Pathfinder results and real tests results, the model could be updated to take into account the features of a particular mine. These simulations could be integrated into the emergency procedure, to provide a quick view of the evacuation procedures. Rescue teams can benefit from these simulations, because it will provide useful information when an emergency intervention takes place. Our partner the Velenje coal mine would welcome the opportunity to carry out such evacuation tests in its mine.

One aspect of great importance for mine operators that has been analysed is smoke evolution when the cross-sectional area gets bigger or smaller and, in general, when the mine's main features change. This study has been carried out with the aid of the FDS software in the present project, however, a further analysis can be done with experimental tests, for example at the Velenje coal mine. Several fire scenarios would have to be selected in order to establish a comparison. These would be simulated to observe the fire evolution and then compared with experimental results using a cold smoke generator.

Another aspect that could be assessed is whether the autonomy of the SCSR is adequate during an evacuation. First a fire location would be chosen. Then, the number of miners that will evacuate the mine have to be put in their place of work and the tests assess the time required to reach a safe place. Then, the ventilation manoeuvre must be activated for the exploitation phase, because this is a very important starting condition for the test. At least during the initial phase of the test, the smoke will head in the same direction as with the imposed ventilation. The results will evaluate the time required to get to a safe place and determine if the SCSR units can provide fresh air to miners till they get to a safe zone.

Geocontrol has experience in the domain of fire simulations in coal mines and is always looking forward to collaborating in projects related to coal mines. Further information about CFD fire simulations and studies carried out by Geocontrol can be solicited.

# Electric Transport Vehicle for Transporting Mechanical Aids

***Wojciech Korski** of Sieć Badawcza Łukasiewicz - Instytut Technik Innowacyjnych EMAG* *presents the work that has been dedicated to developing an electric transport vehicle, a supportive solution to benefit both rescuers in transporting equipment and materials, and other INDIREs solutions during underground rescue actions in coal mines.*

Transport is universally a part of underground rescue actions, be it transport of equipment, materials or injured personnel. Though in most cases not complicated, it is time and efforts that could be used in a more effective manner for tasks requiring training, experience and knowledge. Some of the equipment developed in the INDIRES project require transport to the most immediate vicinity of the rescue action front before effective use, as is the case with the composite roof props and drilling rig with electromagnetic torsional vibrations generator. Thus a development of a transport vehicle, to support the rescue efforts in transporting mechanical aids, became a part of the project.

The aim was to develop a vehicle that can operate in underground coal mine conditions in a situation where power and transport infrastructure in the incident area are unavailable (either damaged or not present in the first place). This transport, to be affective, should have the ability to transport desired loads, and manoeuvrability and terrain crossing properties adequate for given operating conditions. Ease of operation and simplicity of the construction are desirable.

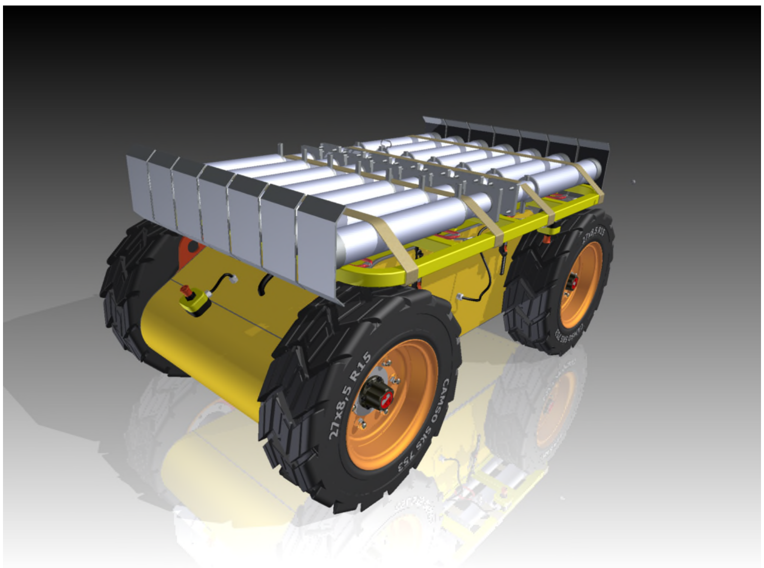
Based on the above premises, an Electric Transport Vehicle (ETV) was developed, and a prototype constructed. To judge user – i.e. rescue personnel – acceptance, the prototype was subject to field testing in a former colliery, now an experimental mine in Poland. Feedback from the rescue personnel taking part in the trials was gathered.

## Functionality and Design Assumptions

Mining conditions impose limits on the size of the solution, as well as provide requirements on the manoeuvrability and terrain crossing properties. A need for easy removal in case of failure or battery discharge must be also taken into account when deciding the size of the vehicle. If not supporting the rescue effort, the vehicle in this state should provide as little obstruction as possible, both in time and efforts to remove this obstruction. This led to the decision to limit the mass of the developed vehicle in respect to the MPI (Mobile inspection Platform), a vehicle developed previously by EMAG and another Polish institute, Łukasiewicz-PIAP. Experiences with the MPI helped to determine the requirements regarding mass and, dimensions, and provided invaluable input regarding the influence of the ATEX compliancy on the final vehicle, an aspect covered in the second issue of the *INDIRES Newsletter*.

A wheeled, all-wheel drive propulsion was identified as providing the best chance to negotiate the terrain with the size remaining within the selected range of the parameters, while retaining simplicity. For this purpose as well, the skid-steering principle (as used in skid steer loaders, or tanks) was adopted for changing the direction of the vehicle, as well as symmetrical construction and bidirectional motion – the constrained, linear space of mine workings favours turning “on the spot”, and reversal of the direction of motion without turning at all.

In the incident area, both transport and power infrastructures will most probably be inoperable, if present in first place. Thus, such a transport vehicle should operate on its own power supply. However, in connection with the limited size and mass, stemming from the conditions it would operate in, also a range/time of operation of the resulting vehicle would be limited. Additionally, charging of equipment in explosion hazard



*INDIRES Electric Transport Vehicle – concept and prototype.*

| INDIRES Electric Transport Vehicle Basic Parameters | |
|---|---|
| DIMENSIONS - CHASSIS (LXWXH) | 2000X1200X800 MM |
| DIMENSIONS - CARGO PLATFORM (LXWXH) | 1560X1200X120 MM (40MM ABOVE THE ETV CHASSIS) |
| MASS (WITH/WITHOUT PLATFORM) | 795/760 KG |
| MAX. SPEED | 1.55/ 2.66KM/H |
| GRADEABILITY | 20 DEGREE (DEPENDENT ON TRANSPORTED MATERIALS) |
| TIME OF OPERATION (MAX.) | 40-45 MINUTES |
| MAX. LOAD CAPACITY | 600 KG (AT 0 DEGREES) 200 KG (AT 20 DEGREES) |

areas, like coal mines, imposed restrictions of its own, resulting in either an extension of the charging time or impermissibility of the process. To partially counter this limitation, it was decided that an exchangeable power supply, i.e. batteries, should be a part of the ETV design. Such operation should be shorter than any charging process possible in the given conditions, easily extending the time of operation of the ETV.

The range of cargo to be transported during the rescue action goes beyond the equipment developed within the INDIRES project scope. Material to be carried to injured personnel, if the need arises, ranges from numerous pieces of smaller equipment (e.g. roof props) or more sizeable devices (e.g. drilling rig), through materials like loose or liquid chemicals in canisters of varying shapes and sizes, cylinders with inert gas, piping and tubing. No universal cargo platform can be developed that would provide both efficient and safe transport of all the above cargo. A reasonable feature, therefore, would be to provide the capability to exchange the platform, depending on the character of the load. This would have an additional benefit of allowing packing of the load in parallel to preparation or maintenance of the vehicle, as well as lowering the level of the platform, making loading more feasible in some instances.

Last, but not least, is the control of the vehicle. It was assumed that the vehicle will be operated by a human operator present in the immediate vicinity. This led to the conclusion that the maximum speed of the ETV should be limited to a walking speed of the operator/rescuer, who would operate the vehicle with a radio operated remote controller, with a limited range, for safety reasons.

## ETV Prototype

The prototype of the developed Electric Transport Vehicle can be seen in the photographs, and its parameters are presented in the table. The INDIRES ETV is a monoblock, symmetrical, steel frame, battery powered, four-wheeled vehicle with a detachable cargo platform mounted on top, operated by a radio remote controller. Each wheel is powered by a dedicated propulsion complex, consisting of a 750W brushless DC motor – with a built-in electromagnetic holding brakes – connected to a parallel gearbox, BLDC motor driver and a rechargeable lithium-polymer battery. This provides the ETV with the ability to move forward and backward with a maximum speed of 2.66 km/h, with an intermediary gear of 1.55 km/h. The motor and gearbox parameters allow a load of up to 600kg with no inclination, or up to 200kg with up to 20° inclination. The 27-inch diameter wheels and no front and rear overhang make it possible to cross obstacles of up to 300mm high. Passing through water of a similar depth is also possible.

In addition to the main propulsion batteries, there are also four auxiliary rechargeable lithium polymer batteries, powering the control systems and radio transceiver. The batteries are arranged into three easily accessible racks, two for the main and one for the auxiliary batteries, allowing for swift exchange. A fully charged complement of batteries allows 40-45 minutes of continuous operation, but this time is dependent on the load, the route of the vehicle, the type of the terrain, and the selected speed.

The dimensions of the prototype allow it to easily move in underground workings, be transported using other means of transport like a suspended monorail, and fit into shaft lift cages, even in older and smaller collieries, as proven during the filed trials. Together with the mass of the prototype, it makes the prototype manageable if it has to be treated as an obstacle. It should be no problem for the rescue personnel to move it aside of need arises. If necessary, towing of the ETV is possible. When the vehicle is turned off or discharged and the brakes hold, it is possible to disconnect the wheels from the gearbox shaft via free-wheel hubs, a solution adopted from all-terrain vehicles. This also helps conserve the battery power during transport to the incident site.

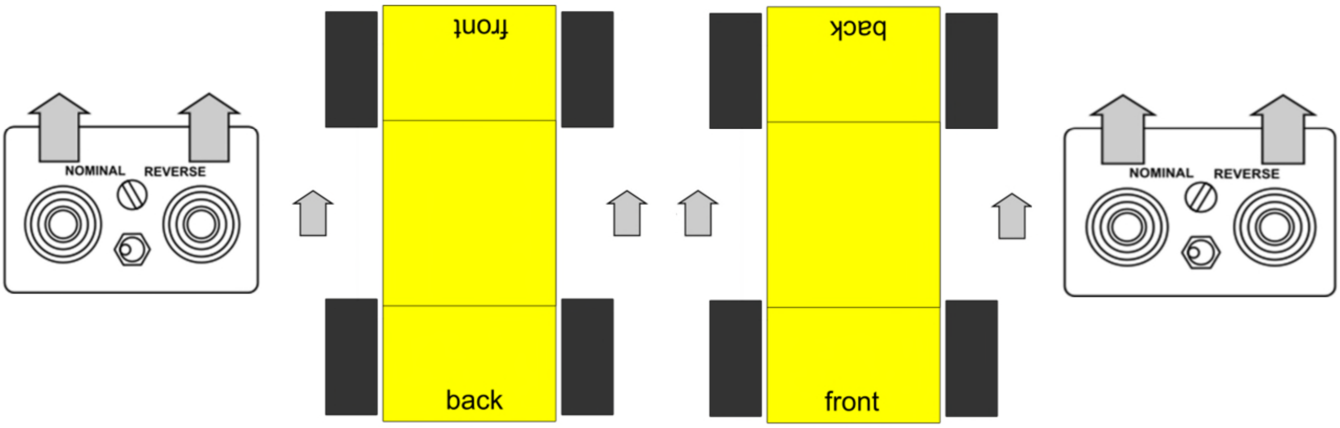
These brakes are one of the safety features of the ETV. To disengage the brakes, main battery power is necessary. The main power is disconnected from the propulsion subsystem in following cases:

- The main switch is turned off.
- Any of the emergency switches are activated (there are two on the vehicle and one on the remote controller).
- The remote controller is out of range with the vehicle.
- Any of the auxiliary batteries is discharged.
- A built-in methane sensor measures $CH_4$ concentration in excess of 2% vol.

The vehicle is operated with a remote controller, equipped with:

- two bi-directional, double notch joysticks (controlling the speed and direction of wheels on one side each),
- a brakes engage/disengage switch,
- a directivity selector,
- and an emergency stop button.

Some explanation is necessary with regard to the directivity selector. As mentioned before, the ETV is symmetrical and can move both forward and backwards. For easier communication and understanding, the ends of the vehicle are marked as “front” and “back”. Ordinarily, tilting the joysticks forward (away from the operator) would cause the vehicle to move forward, tilting them backwards (towards the operator) would cause




*The directivity selector operation. Note the position of the selector and front/back markings on the ETV.*

reversing. However, when there is need for motion in the reverse direction, the operator most commonly turns towards the direction he/she wants to proceed. This is natural and safer for both operator and the personnel in vicinity. In this situation, operation of the joysticks is counter-intuitive, both with regard to the directions and to the sides.

To remediate this, the directivity selector has two positions – NOMINAL and REVERSED. In NOMINAL, the vehicle moves in the direction pointed by the "front" mark when the joysticks are tilted forward. When the REVERSED directivity is selected, the forward tilting of joysticks causes the motion in the direction pointed by the "back" marking. To provide similar help when turning, the sides controlled by the joysticks are also switched.

## Field Trials

The prototype was taken to the "Barbara" Experimental Mine (Mikołów, Poland), which owned by Główny Instytut Górnictwa (GIG), one of the INDIRES project partners. It is an old coal mine which is now operated as a research facility, were solutions and equipment can be tested and research performed in a real-mine environment with limited risk or impact on the productivity.

The goal of the trials was to test the ETV in relevant conditions, while providing opportunity to end users, i.e. mine rescue personnel, to assess the vehicle and provide feedback, as user acceptance was a paramount. For this reason a six-person rescue team from one of the partners, Polska Grupa Górnicza, was invited to take part in the trials. While also providing help with transporting the ETV, the rescue personnel were able to operate the vehicle throughout the trials.

Testing was performed in the underground part of the mine, in various conditions, including inclined, muddy working, with flooded sections, rough ground and galleries containing double railroad tracks, of various cross-sections. During the trials, the ETV was loaded with various equipment and materials, to provide adequate assessment of the vehicle.

The trials included a training session for the rescue personnel (in a long and wide concrete gallery) during which team members familiarized themselves with operating the ETV and its properties. Next, the group proceeded to other parts of the mine, where rescue team members took turns in controlling the ETV while crossing the workings. During the trials, all of the previously mentioned features of the ETV were used. When it was necessary to exchange the batteries:

- The free-wheel hubs were used to move the disabled vehicle to a more comfortable location for exchanging the batteries.
- The cargo platform was detached, to access the batteries, without unpackaging the load.
- -The batteries were exchange for a fully charged ones.
- -The operation took less than 10 minutes.

The manageability of the ETV was tested during the transport to and from the mine, as the older, smaller size shaft lift cage required a change of the ETV position with manual power only.

*The INDIRES Electric Transport Vehicle during field trials.*

During the trials, the ETV had no problem operating in the conditions of the experimental mine. According to feedback provided by the rescuers, the manoeuvrability and terrain properties of the ETV) are adequate, though most felt that the ground clearance should be greater, and the operating of ETV was easy and intuitive. The parameters of the ETV were mostly described as adequate, with an expected exception of the time of operation/range, an aspect being an important barrier in popularizing road-going electric cars.

When asked to assess the usefulness of the ETV, both during the rescue action and in day-to-day operations, the rescuers expressed opinions that ETV would be of considerable benefit, especially during the rescue action and transport of materials. Day-to-day use was seen as less of a possibility, although in some instances a helpful solution. The exchangeable cargo platforms were viewed as a very practical solution, and even ideas for improvements or new platforms – like for transporting gas cylinders – were proposed.

One of the notes would see the ETV equipped with a set of sensors and a camera. The idea, although possible, is beyond the intended (and designed) use of the ETV, but it validates the idea of the INDIRES project, and particularly the resilient sensors and the robotic vehicles as solutions for providing reconnaissance and information from an incident area.

## Current Status

Both the idea and the developed prototype of the INDIRES Electric Transport Vehicle met with positive feedback from the rescue team members and proved itself during the testing in the experimental mine. Despite optimistic results, there are some aspects limiting further use of the ETV in coal mining.

Most obvious is that the testing showed the need for improvements or changes in the construction of the ETV prototype to better serve the various conditions in mining, that can vary from colliery to colliery. Where one mine is relatively dry, others struggle with significant humidity and water inrush Transport lugs and other handles could be improved, as could the time of operation/range. Additional, specialized cargo platforms should be constructed. Nevertheless, the INDIRES ETV prototype is ready for use or further testing.

There is one factor that impedes its use in coal mining, which came into consideration with other solutions developed in the project – the ATEX directive.

Each and every equipment intended for use in explosion hazard areas, such as coal mines, should conform to the requirements of the ATEX directive – regardless of the way it will be made available to the users, including charge-free use for the purpose of a rescue action.

To achieve the planned parameters of the ETV, and with the intended way of use in mind, it was decided to design the ETV partially conformant to the ATEX directive and appropriate harmonized standards. Individual subsystems were either designed or selected to be ATEX-conformant, but the end result cannot be considered so, given that the ETV is stand-alone, battery powered equipment. The designed or purpose-made elements have not been ATEX certified

The ATEX directive does not allow such a construction to be made available for use. However, individual countries' mining legislation provide a doorway for use of non-ATEX equipment, giving the right of decision to mine or rescue action managers or mining authorities. It is rather uncommon that such equipment is used, as this is one of the areas that the risk aversion is clearly visible, especially if conditions are hazardous or dynamic.

Partially ATEX-compliant construction can give the ETV an advantage when a decision is made to allow it into the mine. Coal mining is at a disadvantage compared to other industries utilizing explosion-proof equipment. Development (or certification) of equipment is deemed unprofitable (it is far easier to find a product for ATEX group II than group I), as would the design of solutions dedicated to rescue actions. Some solutions may prove to be unfeasible or impractical with ATEX-compliancy (aerial drones, for example), yet may provide invaluable help during special situations, such as an incident response. For this reason, it would seem reasonable to provide the tools for swift risk assessment of use of non-ATEX or non-coal mine equipment for the purpose of rescue action in given conditions or situations.

Summarizing, the ETV is a useful solution, as proven by the trials and the opinions of the rescue personnel. Though room for further development or modifications is recognised, non-technical impediments for use of this and other solutions intended for rescue actions should be addressed as well. Łukasiewicz-EMAG is open for collaboration in both further development and implementation of the Electric Transport Vehicle (or similar solutions) and research with suggested tools for risk analysis that would benefit the underground rescue actions in coal mining.


*INDIRES ETV remote controller (left) and ETV after the field trials (right).*