Introducing the UNEXMIN Robot for Surveying Flooded Undergound Spaces

*UNEXMIN is an underwater robot that was developed for exploring flooded underground mines. **Steve Henley**, of Resources Computing International Ltd, describes the vehicle and illustrates its achievements by reference to trials in the flooded sections of an archaeological mine and a natural cave.*

Introduction

There are many thousands of abandoned mines in Europe. A large proportion of them were closed not because their mineral resources were exhausted, but for economic reasons – in particular because of competition with lower cost operations in Asia, Africa, and Latin America. Typically the deeper mines became flooded to the local water table level after closure, once pumping was stopped. There is now increasing demand for many mineral raw materials while, at the same time, there are also increasing uncertainties over continuing supply from outside Europe. This is particularly true of minerals identified as “critical raw materials” – see **https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en**.

De-watering mines is very expensive and slow, so an alternative method of exploring is needed. Submersible robots are in routine use in the offshore hydrocarbons sector – and now are being developed for mines. The EU Horizon2020 “UNEXMIN” project has developed a robotic solution which has now been tested in practice in five test sites around Europe, including the Ecton mine, with different characteristics.

It is clear that the same technology could be used for archaeological or scientific studies of flooded underground spaces, including abandoned flooded mines and caves.

The UX-1 Robot

The robot packs a great deal of technology into a pressure hull just 600mm in diameter, or 750mm including the camera domes and its sonar and laser units. It is designed to withstand dives to a depth of 500m. The next paragraphs describe the robot’s main instruments for imaging and making various types of measurements.

There are five cameras which alternate between white LED illumination and ultra-violet light which is used to detect fluorescent minerals.

Laser scanners use a structured light system to produce a three-dimensional point cloud by reflection from the walls, roof, and floor, using the same five cameras.

Four different types of sonar are installed: vertical and horizontal scanning, Doppler velocity log, and sub-bottom profiling. In addition, a forward-looking sonar unit is used for obstacle avoidance.

The robot is designed to be operated either using a tether, with real-time manual steering and decision-making, or autonomously, with pre-programmed route selection and return-to-base logic.

Scientific instruments include:

- a multispectral unit for mineral identification,
- pH meter,
- electrical conductivity meter,
- a gamma ray detector,
- a water sampling unit.

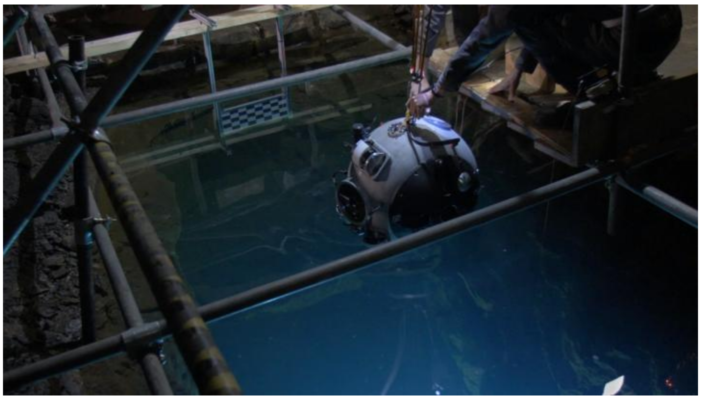
After three initial trials at mines of increasing technical complexity, in May 2019 the UNEXMIN UX-1 robots were used to explore the Ecton copper mine, a complex historic mine in the UK.

Ecton Copper Mine

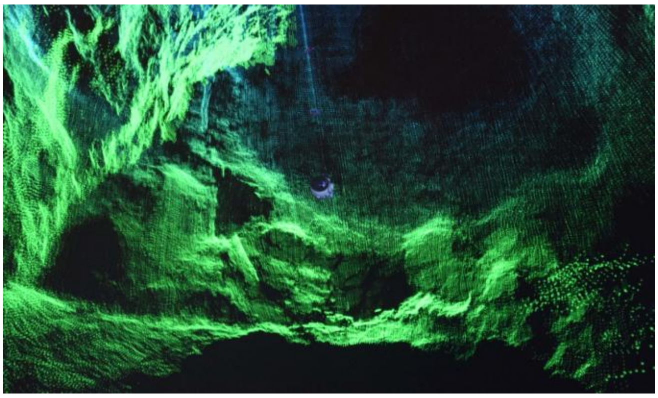
The Ecton Mine in Staffordshire, in the south-west of the Peak District National Park, was at the peak of production in the 1780s and 1790s. It was the deepest mine in Europe, producing copper, lead, and zinc from ore bodies hosted by Lower Carboniferous limestones. At the time it was one of the world's most productive copper mines. This mine was 300 metres deep, below river level, but it has been flooded since the 1850s. Production declined during the first half of the 19th century after the main ore deposit could

UX-1A robot in its cradle on the electric trolley for transfer into Ecton Mine

Dive site setup in the pump chamber in the pumping shaft of Deep Ecton Level



Launching UX-1A in the pumping shaft of Ecton Deep Level.



A sonar survey of part of the large pipeworking chamber. The image of the submersible is a graphic that allows the position and scale of this to be seen.

not be traced any deeper. The flooded part of the mine has never been documented by geologists, and the surviving survey data is in the form of unreliable section drawings that were used for company prospectuses.

There is no possibility that Ecton Mine would be re-opened, since it is a Scheduled Monument, a Site of Special Scientific Interest, and within the Peak District National Park. In addition, it is believed to have no remaining mineral resource of economic value. In general terms we know the ore deposit geology and the mine layout, and the accessible parts of the mine are well understood, but the detail below river level is unknown.

There is only one reasonably contemporary account of the geology of Ecton Mine, by Joseph Watson in 1860 – but that was written two years after the mine had filled with water and it is uncertain whether he ever saw the geology or even visited the area. The mineralisation, principally chalcopyrite, together with galena and sphalerite, occurred mainly in a near-vertical ‘pipe’, the precise form of which is now unknown. However, it is believed to be structurally controlled, and with development of veins and other mineralised structures where the folding is most intense. The rich pipe was worked during the 18th century and the early 19th century, with miners’ attention turning to the smaller and perhaps lower grade vein mineralisation when the pipe deposit pinched out at depth in about 1790.

Despite this, it provided an ideal challenging test environment for robotic surveying.

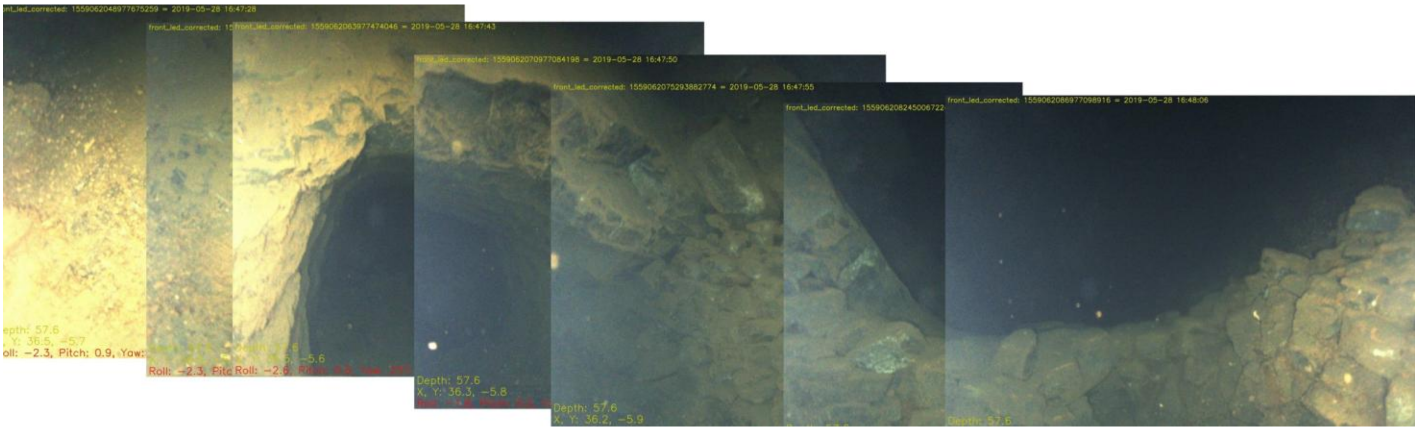
Preparatory Work

Preliminary preparation work was needed at Ecton. Although the mine itself was developed in solid limestone and required no supports, for its outermost 50 metres the adit at river level consisted of stone arching which had a chequered history, and short sections required urgent repairs. In places the roof was strengthened with steel supports, in two places below holes in the arching, and there was a growing bulge in one of the walls. In October 2018, therefore, a major programme of repairs was undertaken, with re-building of the stone arching near the entrance, to allow safe access of researchers and equipment. Within the mine, a ladder way between the adit and Salt’s Level 35 metres higher up, provides the legally required secondary emergency egress route, although it is unsuitable for transfer of heavy and bulky equipment to the launch sites. This required upgrading, with installation of safety netting and modern ropes with a harness system to comply with safety requirements.

The Trials

Two UNEXMIN robots - UX-1A and UX-1B – carried out a total of ten dives between 17th and 29th May 2019 from three launch sites. This yielded an enormous volume of instrumental and image data from two shafts – the main pumping shaft and the winding shaft – and the upper part of the pipe workings. The achievable depths were 125m and 113m in the shafts, which were found to be blocked by rubble at those depths, and 59m in the pipe workings. Data collected included a total of 600,000 colour images, a similar number of UV images, and large volumes of data from the various scientific instruments. The robots were operated in tethered mode for real-time control, using a 400m optic-fibre cable into the mine from a control room at surface.

Because they were designed to have neutral buoyancy, each robot weighed over 110kg. The robots were launched manually using an A-frame pulley arrangement at each of the three launch sites. Progress was monitored at the



Visible image from 57 metres depth in the pipe workings at Ecton Mine. Crosscut on left links to the winding shaft within a few metres. On the right, the pipe workings continue downwards – not yet explored.

Ecton Mine Educational Trust

Ecton Mine Educational Trust owns the mines, mineral rights, and study centre on Ecton Hill in the south-west of the Peak District National Park, near Hartington village. Ecton Mine and the adjacent Clayton Mine were major producers of copper (with some lead and zinc) in the 18th century, unusual for the Peak District mineral field which is known primarily for its lead mines.

It is a registered charity with the principal aims of providing facilities for school and university teachers to run one-day or two-day field courses that will introduce young people to subjects relevant to the minerals industry such as applied geology, metalliferous mining and mineral extraction. The charity also hosts visits to the mine by local interest groups and by interested post-graduate departments of universities.

The Trust actively encourages research collaboration with universities and other researchers. Recent projects have included ground penetrating radar, microseismic surveys, two different types of laser scanning, and clumped isotope studies, as well as the use of ROVs - and of course the UNEXMIN project itself. EMET's facilities are available for such projects effectively free of charge, though since it is manned entirely by unpaid volunteers, donations towards upkeep of its facilities are always welcome! It owns the mines in Ecton Hill, and as the owner also of the mineral rights it is responsible for safety of the public - this includes monitoring and maintenance of the many shafts and other surface features related to the extensive history of mining at Ecton. Further information is available from **www.ectonmine.org**.

surface by real-time optic-fibre data feeds from the sonar and camera systems. The robots were driven using eight thrusters – four mounted on each side – and a submarine-style oil-filled ballast unit, with attitude controlled by a pendulum which was weighted by the main power supply batteries. The tether, initially a standard Ethernet cable, was later replaced by a lighter and more flexible optic fibre cable. Because of the neutral buoyancy, and the use of on-board thrusters to move the robots, this cable did not need to have high physical strength.

Geology and Archaeology

The image data from each camera in each dive were combined to provide a set of videos to make it easier to interpret both the geological and archaeological features.

Current knowledge of the history of Ecton Mine is fully explained by Barnatt (2013). The geology consists essentially of folded Lower Carboniferous limestones, either thickly bedded, or thinly bedded with shales in some horizons, and occasional thin clay wayboards derived from volcanic ash. Joseph Watson's account (1860) emphasises the importance of structural controls – in particular so-called "saddles", which we can interpret as anticlinal or synclinal folds, with mineralisation preferably in the fold limbs and in fractures close to the axial planes of folds. Ford (2000) concludes, from historical descriptions, that the main pipe deposit was most likely in the form of a stockwork or breccia, but there was no evidence for this in the parts accessible above water level. It is perhaps pertinent, however, that there is a small area of stockwork in the adjacent Clayton Mine with the usual pipe-workings minerals rather than just calcite veinlets. Since the deposit itself is mined out, there is little supporting evidence for this from the submersible data.

However, there are definitely some areas in the shafts which could be best described as stockworks – masses of rock cut in all directions by calcite veinlets. Porter (2004, p.19-22) tries to make sense of Watson's confusing description of the deposits, and some of the 'saddle' (folding) and fracture features he describes do seem to match structures which are seen in the submerged parts of the shafts.

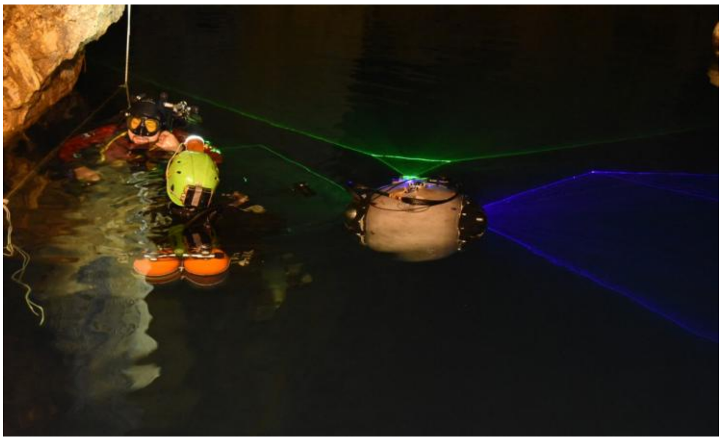
The mineralised pipe deposit was apparently not continuous but formed a series of eight masses. These were mined separately in huge caverns which are said to lie one above another, vertically, as quoted by Porter (2004, p.101). from the journal of John Harpur, c.1767-1770. However, when Harpur visited, the workings were only about 155m deep and there would have been more below this depth.

Sonar surveys in the robot exploration of the pipe working, to a depth of 58 metres, show one such vast cavern, now partly filled by rubble, estimated to lie up to 20 metres thick on the floor at one end. The total height of this mined chamber was perhaps up to 40 metres. Others – or maybe parts of the same one – are glimpsed through large openings in the sides of both the pumping shaft and the winding shaft, at depths from 53m down to 110m. Not all would have been the same size, so it is reasonable to expect to find more of these openings down to the maximum 300m reported depth of the mine.

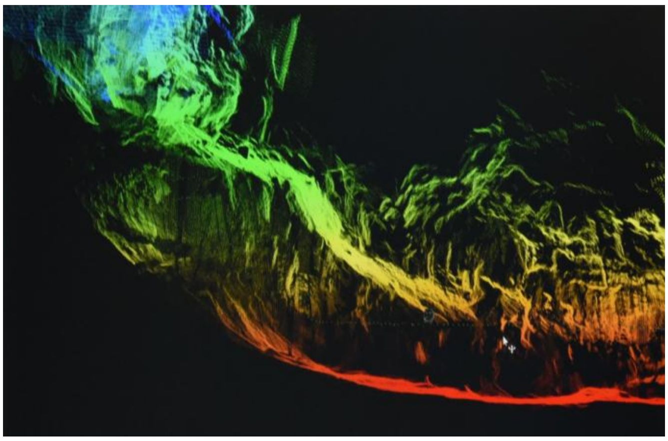
Molnár János Cave, Budapest

The next mission was in the Molnár János Cave, Budapest, Hungary.

The cave system was formed in Eocene marl and limestone and it is the biggest underwater thermal cave in Hungary. The cave was named after János Molnár who discovered the entrance tunnel in 1856, and made the first chemical analysis of the water. He assumed the existence of a large



UNEXMIN submersible UX-1 at start of a dive in Molnár János cave, with SLS (structured light system) lasers switched on

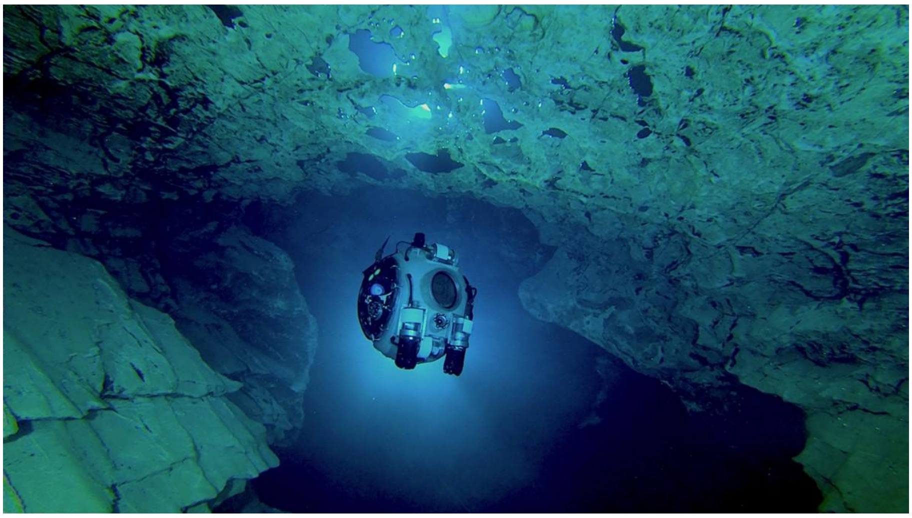


Real-time sonar mapping of Molnár János cave underwater cave system beyond the part then known, in his descriptions. In 1990 an expedition discovered a big chamber. approximately 30 × 30 × 15m. This was only a few metres below an already existing artificial tunnel which was made in the 60s. In 2002 they discovered further new passages, so they decided to connect artificially the large chamber and the tunnel, thus making a new entrance for divers into the cave system. The known system extends 4km horizontally, and is up to are 57m deep. There are about 7km of passages.

It has a unique ecosystem with endemic crabs due to the 20–23°C temperature of the water, which is used in the Lukács Spa, next to the cave. The air temperature inside the tunnel is 19-20°C throughout the whole year. Divers from all over the world are visiting the cave continuously.

During the Molnár János mission, both the UNEXMIN robots made dives in the tunnels. For launch, the newest entrance in the large chamber was used and all the dives ended at the same point. The control room was set up outside the cave in an unused restaurant building on the bank of the Malom-lake (Mill-lake), which is approximately 200m from the launch site. The robots carried out 3D mapping in different parts of the cave. There were navigation lines for cave diving purposes in all the passages, and local dive masters helped to navigate the robots underwater.

The UX-1 robots performed in-situ measurements with the pH, and electrical conductivity sensors, and with the sub-bottom profiler unit. The data collected was being post-processed as this article was being written, but will be available at the end of September 2019 for virtual reality applications.



UX-1 submersible within Molnár János cave. The silvery patches above the robot are air trapped under the limestone roof of the cave.

Acknowledgements

The project is a joint effort of 12 teams from seven EU member states whom are thanked for their hard work and expertise.

Particular thanks go to the following. First to Norbert Zajzon, the UNEXMIN team coordinator, from Miskolc University in Hungary, who managed the various European contingents with diplomacy and skill. Second, to Carlos Almeida from INESCTEC in Portugal, who did the excellent job of steering the submersibles and who was often at the forefront when the repair teams were working between missions.

The geological and archaeological interpretations at Ecton Mine are the result of detailed work by Richard Shaw and John Barnatt respectively. Historic England is thanked for allowing the project to be undertaken within the Scheduled Monument.

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Future Plans

The UNEXMIN consortium intends to continue development of such instrument-laden submersible robots. We also plan to provide a service using these robots for surveying flooded underground mines and for other similar applications such as the inspection of underground water reservoirs without the need to empty them to provide for human access.

The need for such a service is amply demonstrated by the very large number of flooded tin mines in Cornwall and Devon alone. Many hundreds of mines closed in the 19th century, not because their resources were exhausted, but simply as a result of competition from low cost tin producers in south-east Asia and South America, and copper mines in central Africa and Chile. Reconnaissance surveys without the cost of de-watering and the risks of using human divers would provide vital information for decisions on the potential for detailed re-evaluation of these mines, as well as others throughout Europe.

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Stephen Henley

Dr Stephen Henley is a geologist who has worked in public and private sectors since the 1970s, principally in computer applications related to mineral exploration, geological modelling, and mine planning. He was founder and developer of the DATAMINE mining software system in the 1980s, and has worked as a geological consultant worldwide; from the 1990s this has included many projects in the former Soviet Union.

A trustee and former chairman of PERC (Pan-European Resources & Reserves Reporting Committee, www.percstandard.eu) , and current president of the Brussels-based International Raw Materials Observatory (www.intraw.eu), in recent years he has concentrated on research and voluntary activities, including several EU projects of which UNEXMIN is one of the most recent. He is now working as a participant in a major new project, ROBOMINERS, started in June 2019, for development of bio-inspired mining robot systems applicable to smaller mineral deposits.