Robots explore flooded mine

A new type of submersible robot could provide a more accurate picture of the state of historic flooded mines and help evaluate whether they may be worth reopening. *Stephen Henley* reports on field tests in Staffordshire

There are thousands of abandoned mines in Europe. Many were closed not because their mineral resources were exhausted but for economic reasons – in particular competition with lower-cost operations in Asia, Africa and Latin America. Typically the deeper mines ended up flooded to the local water-table level once pumping had been stopped. At the same time, there is now growing demand for mineral raw materials while uncertainties over continuing supply from outside Europe are increasing, particularly for substances identified as "strategic raw materials".

De-watering mines is a very expensive and slow process, so an alternative method of exploring them is needed. Submersible robots are routinely used in the offshore oil and gas sector, and are now are being developed for mines. The EU Horizon 2020 UNEXMIN project has developed a robotic solution, the UX-1 robot, which has been undergoing a series of field tests. The project, a joint effort of 11 teams from seven EU states, started in 2016 and is due to end in October 2019.

The UX-1 robots

The robot packs a great deal of technology into a pressure hull just 60cm in diameter, or 75cm including camera domes and its sonar and laser units, designed to withstand dives up to 500-metre depth. There are five cameras that alternate between "white" LED illumination and ultra-violet light to detect fluorescent minerals.

The unit features three different types of sonar – vertical and horizontal scanning, plus sub-bottom profiling. 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. A forward-looking sonar unit is used to avoid obstacles.

The robot is designed to be operated either using a tether or autonomously. Scientific instruments include a multispectral unit for mineral identification, pH meter, electrical conductivity meter, and a gamma ray detector, as well as a water sampling unit.

Ecton copper mine

After three initial trials at mines of increasing technical complexity in Finland, Slovenia and Portugal, in May 2019 the UNEXMIN UX-1 robots were used to explore a complex historic mine in the UK, the Ecton mine in Staffordshire, in the south-west of the Peak District National Park.

Ecton was the deepest mine in Europe in its heyday of production in the 1780s-90s, producing copper, lead and zinc. At the time, it was one of the world's most productive copper mines. Production declined during the first half of the 19th century, when the main ore deposit could not be traced any deeper. Ecton is 300 metres deep, below river level, and has been flooded since the 1850s. The flooded part of the mine has never been documented by geologists, and the surviving survey data is in the form of unreliable extracts that were used for company prospectuses.

Before conducting any field trials with the robots at Ecton, preliminary preparation work had to be carried out. 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 needed urgent repairs. The roof was strengthened with steel supports in places – 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 repair programme was undertaken, with rebuilding of the stone arching near the entrance, to allow safe access for researchers and equipment. Inside the mine, a ladder way between the adit and the salts level 35 metres higher up, provides the legally required secondary emergency egress route. This required upgrading with the installation of safety netting and modern ropes with a harness system to comply with safety requirements.

> **"Reconnaissance surveys without the cost of de-watering would provide vital information on the potential to re-evaluate the hundreds of flooded tin mines in Cornwall and Devon alone that closed in the 19th century"**

In May 2019, the UNEXMIN team spent three weeks at Ecton, carrying out a series of ten dives using two robots. The mine is an ideal challenging test environment for robotic surveying, even though there is no possibility of it being reopened, since it is a scheduled monument, a site of special scientific interest, and lies within the Peak District National Park. In any case, it is believed to have no remaining mineral resource of economic worth.

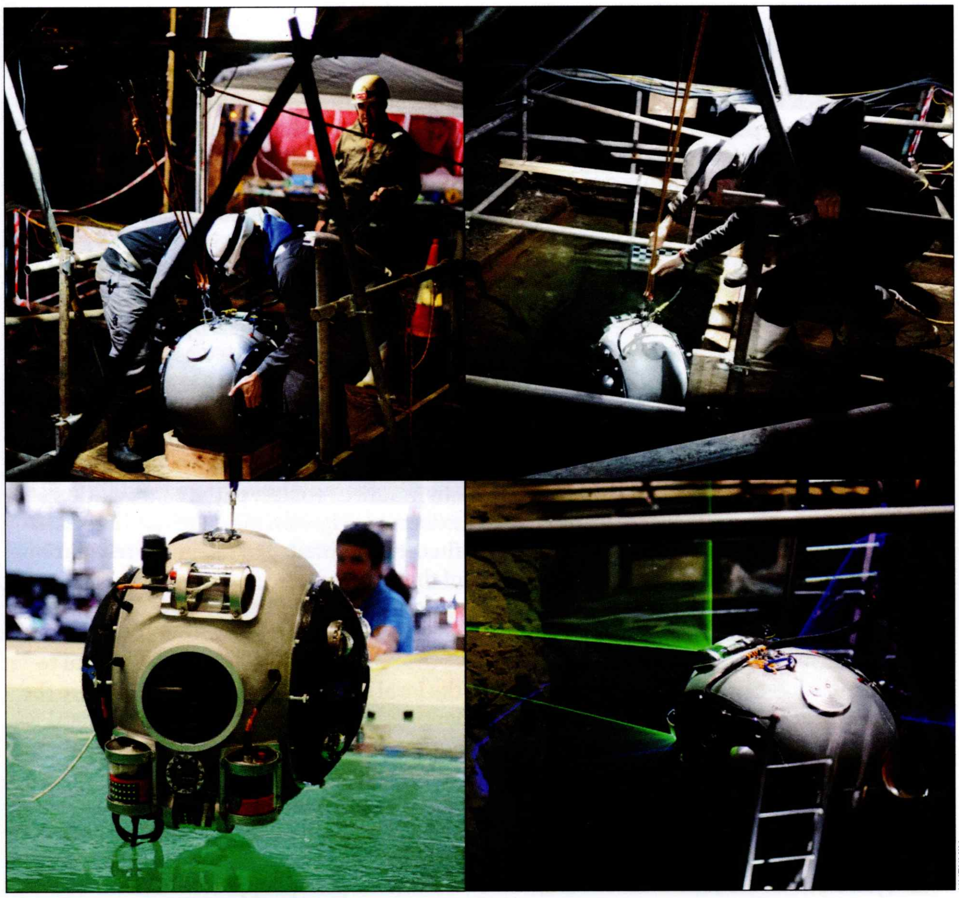
Although in general terms we know the ore deposit geology and the mine layout, and the accessible parts of the mine are well understood, the detail below river level is unknown. The only reasonably "contemporary" account of Ecton mine's geology, by Joseph Watson, was written in 1860, two years after the mine had filled with water, and it is uncertain whether Watson ever saw the geology.

The mineralisation, principally chalcopyrite, together with galena and sphalerite, occurred mainly in a near-vertical "pipe", whose precise form is now unknown but believed to be structurally controlled, with development of veins and other mineralised structures where the rocks are at their most folded. The rich pipe was worked during the 18th century and 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.

The trials

There were ten dives of the two robots between 17 and 29 May. These yielded an enormous volume of data from the main pumping shaft and the winding shaft, covering the upper part of the pipe workings, to 125-metre and 113-metre depths in the shafts (which were found to be blocked by rubble at those depths), and to 59 metres 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 scientific instruments. The robots were operated in tethered mode for real-time control, lowering a 400-metre fibre-optic cable into the mine from a control room at surface. As they were designed to have neutral buoyancy, each robot weighed more than 110kg.



UNEXMIN

The UX-1 robot is prepared and carefully lowered into the shaft at Ecton mine to capture large volumes of data from its extensive instrumentation (clockwise from top left)

The robots were launched manually using an A-frame pulley arrangement at each of the three launch sites. Progress was monitored at surface level by real-time data feeds from the sonar and camera systems, and was driven through eight thrusters (four mounted on each side) and a submarine-style oil-filled ballast unit, with altitude controlled by a pendulum weighted by the main power supply batteries.

The tether, initially a standard ethernet cable, was later replaced by a lighter and more flexible fibre-optic 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 images 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.

The current knowledge of Ecton mine's history is fully explained by Peak District National Park archeologist John Barnatt's 2013 book *Delving Ever Deeper: The Ecton Mines Through Time*. The mine's 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. Watson's 1860 account emphasised 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.

An article published by TD Ford in *Mining History* in 2000 concluded 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. [However, 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 that could be best described as stockworks – masses of rock cut in all directions by calcite veinlets.

A 2004 work by Linsey Porter tracing Ecton's 18th-century history tries to make sense of Watson's confusing description of the deposits, and some of the "saddles" (folding) and fracture features he describes do seem to match structures seen in the submerged parts of the shafts.

The pipe deposit was apparently not continuous but formed a series of eight masses, mined separately in huge caverns that are said to lie above another, vertically, as quoted by Porter from the 1767-1770 journal of John Harpur, although when Harpur visited, the workings were only about 155 metres deep and there would have been more below this depth.

Sonar reflections 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 53 metres down to 110 metres. Not all would have been the same size, so it is reasonable to expect to find more of these openings down to the maximum 300-metre reported depth of the mine.

Future plans

The UNEXMIN consortium intends to continue developing such instrument-laden submersible robots and to provide a service using them for surveying flooded underground mines and for similar applications, such as 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: hundreds of mines closed in the 19th century 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 would provide vital information for decisions on the potential for detailed re-evaluation of these mines, as well as others throughout Europe. ■

Stephen Henley owns Resources Computing International, which coordinates the work of the 4dcoders group to develop post-processing software for the data returned by the submersibles