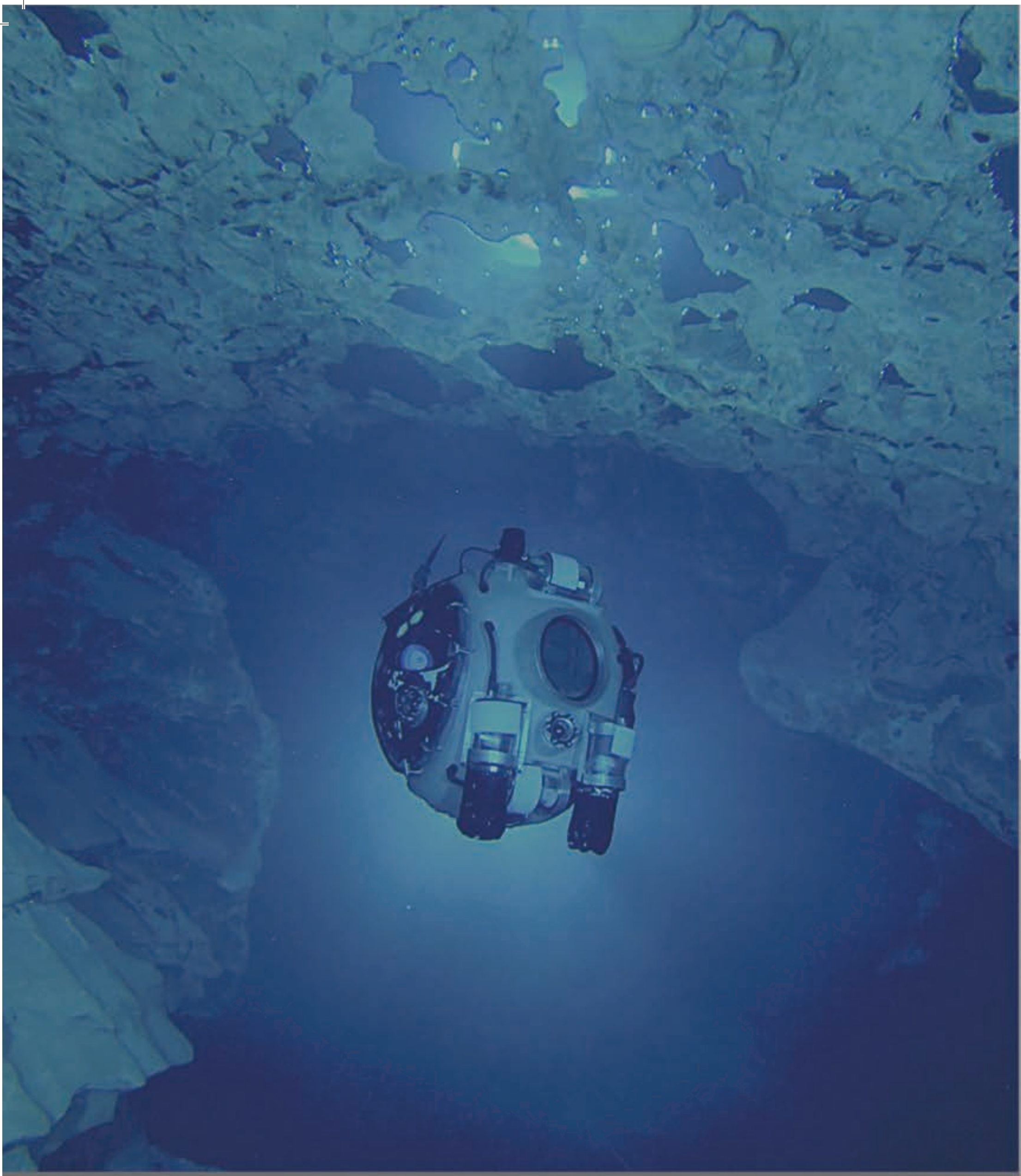


UNDERWATER
EXPLORER
FOR
FLOODED
MINES

UNEXMIN

UNEXMIN PROJECT BOOKLET

SEPTEMBER 2019

UNEXMIN CONSORTIUM

Message from the Coordinator

It has been a privilege to lead and coordinate this outstanding and innovative research team that has developed the UNEXMIN technology platform. Working with this truly European consortia from research, industry and education, in the laboratories and on the different field trials has been a great experience.

I invite you to read further this booklet and learn about the four-year journey of the UNEXMIN technology and its future, and how it aims to address the future raw material demands of our European society.

Norbert Zajzon

Introduction to UNEXMIN

In Europe, it is estimated that there are around 30,000 closed mine sites. Many of these may still have considerable amounts of essential raw materials. However, most of these closed mines are now flooded and the last information of their status and layout is decades or more than a hundred years old. The complex underground layout, topology and geometry of most underground mines, make it impossible to do any surveying by conventional or remotely controlled equipment. The main objective of UNEXMIN was to develop an autonomous multi-platform Robotic Explorer with tools for exploration and 3D mine mapping of flooded and deep mines, otherwise inaccessible, in Europe. As a result, UNEXMIN's pioneer technique can open new exploration scenarios for abandoned mines in Europe as well as worldwide.

Results achieved

With the overall aim to push the EU to the forefront in sustainable minerals surveying and exploration, to increase its capacity to re-evaluate its abandoned mines for their mineral potential, with reduced exploration costs and increased investment security for any future mining operations, and, finally, to help to document and safeguard Europe's unique mining heritage, UNEXMIN focused on reaching the following specific objectives.

- Design and build a platform of Robotic Explorers for 3D mapping of flooded deep mines
- Demonstrate the operation of the prototypes at a set of representative test sites
- Develop a research roadmap in support of further technology development
- Develop commercial services for exploiting the technology

Work under UNEXMIN (besides project management and project communication & dissemination) is divided into the following seven core work packages (WP):

WP1 – Robotics functions validation
This WP designed and validated key robotic components and functions involving the mechanical aspect of the robot, such as movement, control and resistance.

WP2 – Scientific instrument design and adaptation
WP2 defined, adapted, tested and calibrated the various scientific instruments that the UX-1 robot employs, including water sampler, sonars and multispectral cameras.

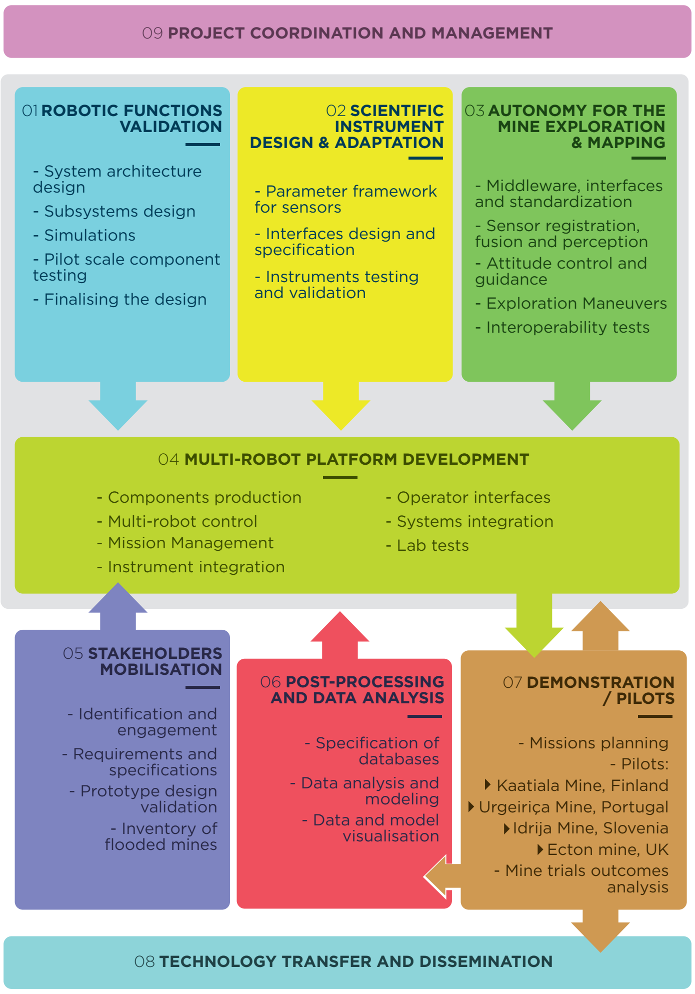
WP3 - Autonomy for mine exploration and mapping
During this WP the autonomy functions of the system were developed and integrated. Together with autonomy, the mapping functionalities of the system were also created.

WP4 – Multi-robot platform development
It was during this WP that the new class of mine explorer service robots was built, capable of surveying flooded underground mine sections working individually or as a group. Development work was continuous and incremental, always converting the outcomes of field investigations into the development of upgrades. The end result is a robust exploration platform.

WP5 – Stakeholder mobilization
This WP mapped, understood and processed stakeholder views and requirements. As a part of this activity a detailed stakeholder database was created as well as an extensive database of flooded mines in Europe. The main objective was to adapt the robot design to stakeholder needs.

WP6 – Post-processing and data analysis functions
WP6 developed solutions to convert raw data recordings from multiple sources into 3D datasets so that the data can be used to increasing our understanding of mineral deposits formation, including the development of geo-models of mineral deposits and other useful tools.

WP7 – Demonstration / Pilots
The main objective of this WP was to test the prototype robots' capabilities under real-life conditions and at the same time demonstrate how this technology can address the needs of customers and end-users.



The Multi-Robot Platform

The structural design of the UX-1 robots and their mechatronic systems differ substantially from traditional designs seen in ROVs (Remotely Operated Vehicle) and AUVs (Autonomous Underwater Vehicle) as UX-1 employs integrated pressure hulls. Furthermore, UX-1 uses single pressure hull design instead of open frame design typical of other miniature submersibles. The pressure hull is divided into several separate pressure tight compartments to improve the survivability of the submersible. The integrated pressure hull enables small size and light overall weight with a large dry compartment necessary for certain systems and payload.

The propulsion system of UX-1 employs eight separate thrusters. The number of thrusters give the propulsion system tolerance to faults and damage, important for operation in unknown, potentially hazardous environments. Other atypical features in UX-1 include an active hydraulic ballast system and a pendulum system. The active ballast system is used for changing the buoyancy of the submersible and can be used to control the vertical movements of the submersible and to compensate for compression of the pressure hull caused by depth and changes in buoyancy caused by temperature and/or salinity. The pendulum system is used to pitch the bow of the submersible up and down when moving through vertical passages such as mine shafts.

CHARACTERISTICS OF THE ROBOTS

- Max operational depth: ~500 m
- Shape: spherical
- Size: ~ 0.6 m diameter
- Weight: 112 kg
- Neutral buoyancy
- Power consumption: 250-400 W
- Max speed: 1-2 km/h
- Autonomy: up to 5 hours
- Thrusters power: 2-5 kgf

Operational Robots

The UX-1 operational robots integrate the onboard computational capabilities for sensor processing, navigation, exploration of the environment and data logging.

Due to space restrictions the scientific instrumentation is divided among the vehicles, and it is used according to the specific mission requirements. All vehicles have navigation sensors, locomotion, ballast and pendulum systems and a computational subsystem. This consists of four onboard computers responsible for the global robot navigation, for sonar data and vision data processing.

The robots explore the environment by recording estimated location, and all the sensor data. Vehicle navigation is obtained from the sensor fusion of INS (Inertial Navigation System) and DVL (Doppler Velocity Log) data to provide an initial navigation solution that is then used in a SLAM (Simultaneous Localization And Mapping) framework in conjunction with detected features in the environment to provide the vehicle positioning. During the exploration process a real-time map of the environment is constructed from the multibeam sonar data and it is complemented with structured light data when available.

The scanning sonar is mainly used for obstacle avoidance.

Instrumentation

The robot sensors have two purposes: providing information for the vehicle navigation and collecting scientific data.

These can be divided in two groups: the general navigation and mapping sensors and the scientific instrumentation payload used for specific environment sensing related with geology.

The environment is perceived with sonar sensors, and with vision based sensors (cameras and structured light system) whenever the water turbidity allows. The INS and DVL sensors are used to navigate the robot in conjunction with information retrieved from the environment.

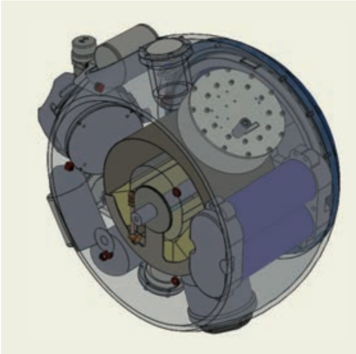
The instrumentation sensors are used according to the specific exploration mission in order to obtain further characterization of the explored site. This information can be useful in determining relevant geological characteristics or to provide valuable clues for the existence of minerals of interest.

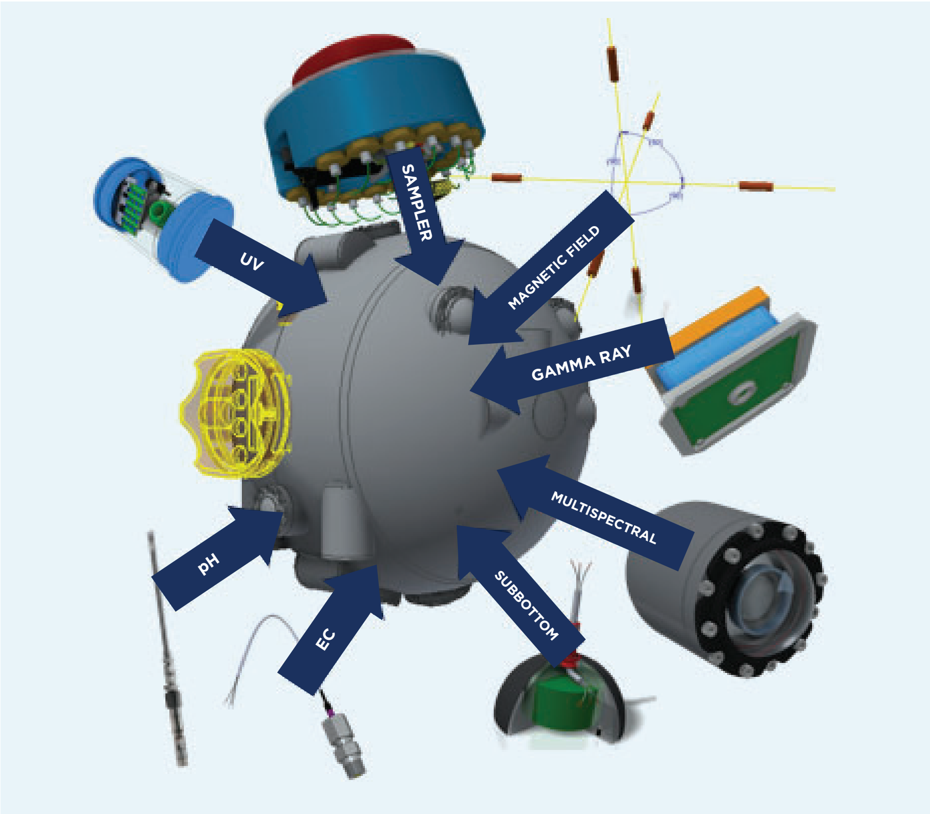
NAVIGATIONAL INSTRUMENTATION

- Multibeam sonar
- Scanning sonar
- Digital cameras (5)
- Structured light projectors
- Doppler velocity sensor (DVL)
- Inertial Navigation System (INS)
- Scanner and lasers

SCIENTIFIC INSTRUMENTATION

- pH and electrical conductivity units
- Temperature and pressure sensors
- Water sampler
- Magnetic field units
- Gamma-ray counter
- Sub-bottom profiler
- Multispectral camera
- UV fluorescence camera



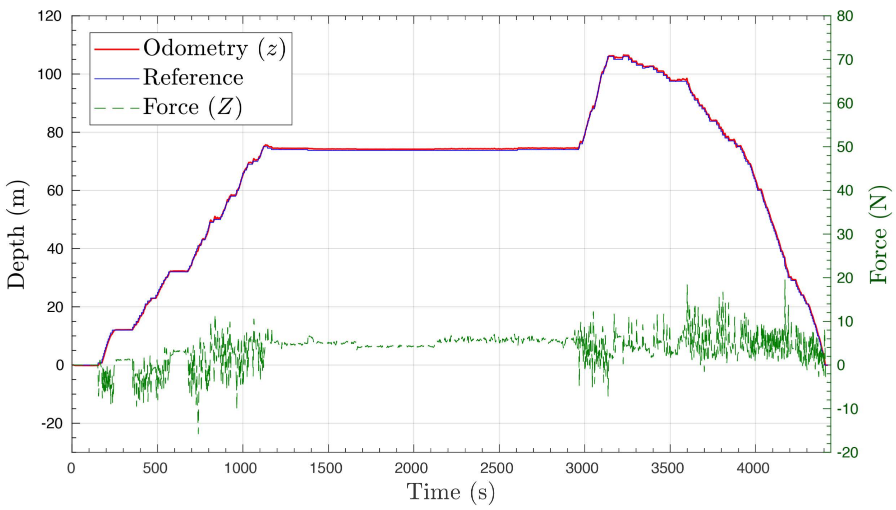


Autonomy

The inaccessibility of the operational environment and lack of communications with the surface makes autonomy a critical and primary objective of the project in order to allow the UX-1 robots to carry out flooded mines exploration. Most of the time, the robots have to navigate in a semi-structured but unknown environment, with no information about possible obstacles along the path. Hence, the robots implement an exploration strategy that consists of mapping the tunnel section immediately ahead and advancing while avoiding obstacles and tunnel walls. Different advanced 3D motion control techniques have been developed and tested for this purpose.

To assess the guidance, navigation and control system, navigation during trials was aided by a pilot: key waypoints were sent by a human operator, and the robot could autonomously generate the path and navigate to the waypoint. More than 350 meters of tunnels have been explored during field trials, and counting multiple dives the robot has navigated more than 1000 meters underground.

Autonomy also means self-status assessment and related mission re-planning and system configuration. These will allow the robot to be aware of its status and of its capabilities to fulfill the mission, having the ability to self-configure for optimal performances (e.g., after a failure in a thruster) as well as decide which mission goals are achievable and re-plan its mission accordingly.

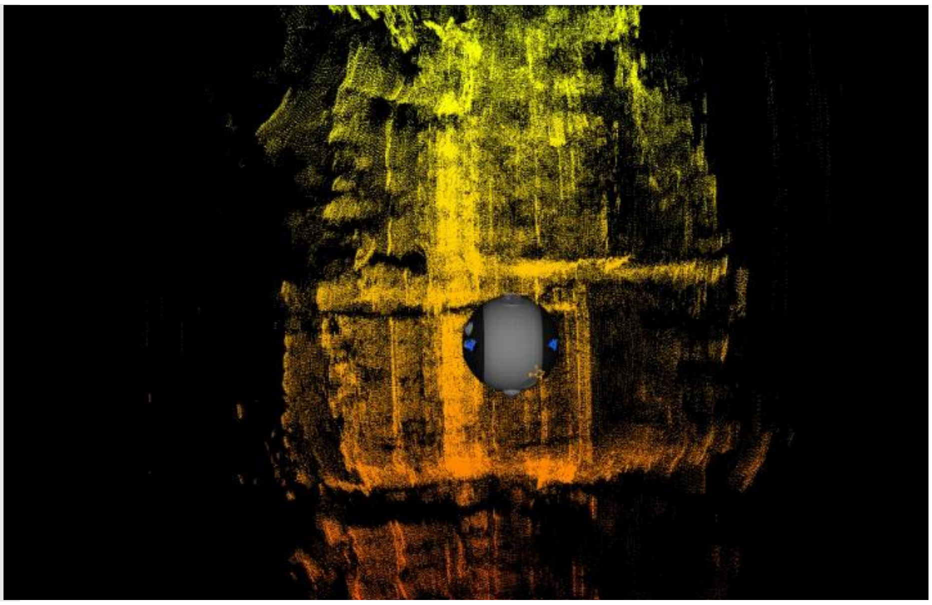


The depth graph, comparing the odometric depth and depth determined by navigation software and thruster force.

During the months of March and April of 2019, the UNEXMIN technical teams visited Portugal for the 3rd trial, at the Urgeiriça uranium mine. The maximum depth of the mine is 450m, which allowed the robot and its equipment, to be tested in harsh conditions including high pressure and acidic water.

Explore the shaft: the figure shows a real-time virtual reality model of the part of the shaft (coated with wooden support), created from the obtained point cloud data from different sensors.

The Urgeiriça mine provided a good opportunity to test the robots maneuverability in the mine's shaft as well as in mine's tunnels. Since Urgeiriça is a uranium deposit, instruments for detecting radioactive minerals were also planned to be tested at this site (i.e. gamma-ray counter).



Testing the prototypes

To get a better understanding of how the prototype robot behaves in real-life environments, and how the whole process of collecting geological and archaeological data can be practically conducted in mine environments, five different trial sites were selected. The selection of the test sites was based on the harshness of the conditions at each trial site, starting with the easiest, most open and accessible site and with gradually increasing difficulty.

All five trials were successful, the robot's navigational systems were tested and real time map building and basic autonomy of the robots were achieved. During the tests the prototype robots UX-1a and UX1-b collected valuable geological and archaeological information using visual, UV, multispectral and other scientific instruments. The knowledge and experience gained during the field trials will help developers to understand what are the limitations of the system and what improvements can be done in the future. Overall the trials have proved that the system is capable of operate in mine environments and is able to explore flooded underground areas which are otherwise very hard, unsafe or even impossible to reach by any other method.

A field mission with the UNEXMIN technology can last from 1 up to 3 weeks with a team of 8 operators and support engineers. During each dive an approximately 1Tb of data is collected by the UX-1 system that is later post-processed to create geological reports and visualizations.

9 Steps Mission

1. Setting up the test site to enable the UNEXMIN team to conduct the test dives safely (access to the launch zone, setting up platforms, winch systems, etc.).
2. Arrival of the technical team, the robot and all of the equipment necessary for the tests.
3. Setting up the control room, launch site, communication and cameras.
4. Safety inductions at the testing sites so team members familiarise themselves with the site's safety rules.
5. Teams are divided between the control room and the launch site.
6. Conducting surveying missions according to the daily schedule, taking into account the specific missions objectives.
7. Daily de-briefings regarding the tests that were carried out that day and plans for the next.
8. Packing up and sending the equipment to the next location. Team members leave the site.
9. Data post-processing and preparing a geological report, a virtual-reality model of surveyed parts of the mine (point cloud), videos from UX-1 cameras and extracting other useful geo-scientific materials for mine exploration.

Completed missions

1 KAATIALA MINE, FINLAND (JUNE 2018)

- Pegmatite mine
- Open-pit and small underground part
- First tests of robotic functions and components in a simple mine environment

2 IDRIJA MINE, SLOVENIA (SEPTEMBER 2018)

- Mercury mine, UNESCO World Heritage site
- Movement, control and 3D mapping to explore shafts in confined environments

3 URGEIRIÇA MINE, PORTUGAL (MARCH/APRIL 2019)

- Uranium mine in granite pegmatite
- Maximum depth of 450m allowed the robot and its equipment to be tested in harsher conditions

4 ECTON MINE, UK (MAY 2019)

- Cu - (Zn-Pb) mine (Mississippi Valley type mineralization) flooded in 1858 and never previously resurveyed
- Exploration and survey of part of the flooded area of the mine, up to 125m depth with dives in 3 shafts

5 MOLNÁR JÁNOS CAVE, HUNGARY (JUNE/JULY 2019)

- Cave system reaches up to a length of 6km with sections up to 100m depth

Kaatiala mine, Finland (June 2018)
In this particular mission objectives were to test the prototype's basic functions and to record raw data from the navigation sensors to validate in post processing and tune the navigation fusion algorithms. The scientific instrument array, as well as the efficiency of data retrieval and processing were also tested.

Idrija mine, Slovenia (September 2018)
Idrija's mission objectives were to test the prototype operation in a much more challenging real-life environment. The Idrija mine is an underground mine with limited visibility, narrow passages, limited air flow and no electricity. As the visibility in the water was very low due to the mines' murky water and the amount of debris floating in it, the operators had to rely solely on the robots' navigational systems while navigating the robot.

Urgeiriça mine, Portugal (March/April 2019)
In Urgeiriça the mission objectives were to test the prototype operation in a deep underground mine with accessible entrances to numerous mine levels. This provided the UNEXMIN team with the opportunity to test the robots maneuverability in the mine's shaft as well as in mine's tunnels. In total 18 dives were made at Urgeiriça, with the maximum depth reached at 106.5 m.

Ecton mine, UK (May 2019)
The ancient copper mine in Ecton gave the team the opportunity to re-enter old mine workings and collect valuable geological information concerning the orebody. As some parts of the ancient coper mine in England haven't been accessible for hundreds of years after it was flooded one of the main objectives was also to collect archaeological information from this site and to record any artefacts that are still lying in the mine. The three main shafts and some of the most important mining areas were navigated and mapped by the UX-1 system. The deepest point achieved was 125m.

Molnár János cave, Hungary (June/July 2019)
The Molnár János pilot was the selected location to test and improve the prototype's autonomy. This site also represented a new testing environment for the project team, where the UX-1 robots were yet to be tested. In total, 10 autonomous navigation missions were successfully achieved.

Mapping

One of the main tasks of the robot is to obtain an accurate map of the explored site. The mapping process is important for the final data product as well as during the mission as it allows the robot to navigate safely in the mine.

Two types of maps are produced: a real time map used for navigation purposes and an offline detailed map produced in post-processing of the recorded data. The map is obtained using a range of information from two types of sensors: acoustic and structured light vision based sensors. In both cases the detected environment point cloud is registered relative to the vehicle position from the navigation system.

Acoustic data is useful when the water turbidity reduces visibility and for larger sensing distances (such as when mapping in large spaces). Structured light is used for short distances (less than 5m) to provide a very precise (on the order of millimeter) map.

Creating data

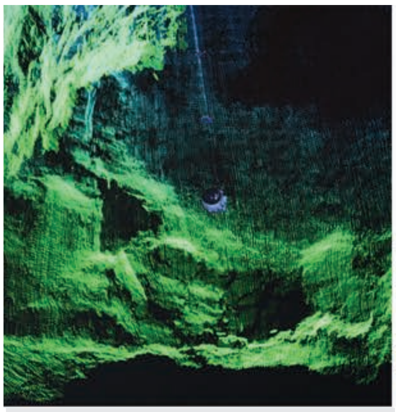
The data sets are all generated within the robot, by its navigation systems, its cameras, and its scientific instruments, and stored in a high-capacity memory unit. Data is downloaded from the robot's internal memory system at the end of each dive mission. When operated in tethered mode, just a small subset of the data - robot status, position, sonar and laser responses and camera images - can be retrieved in real-time to allow instant decisions by the mission controller.

Analyzing the data

Data from the robots is held in 'bag' files which must be unpacked and decoded to extract each type of data, whether numeric or as images (vectors, images, others). Data from the sonar units and from the laser-based structured light system are used to generate three-dimensional point clouds that can be used as a basis for models of the mine geometry. Cameras produce images - full-colour photos, ultra-violet images to detect fluorescent minerals, and multi-spectral data for further mineral identification - and these images can be combined into video reconstructions of the dive. The data sets can then be processed using a wide range of graphical and statistical applications to assist in the scientific interpretation.

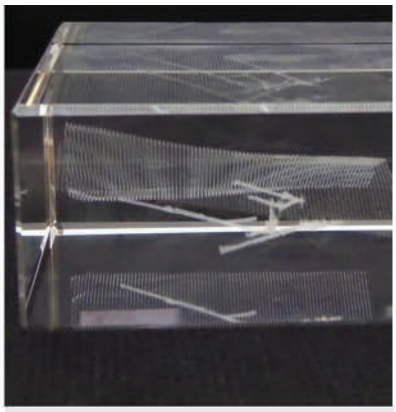
With processed data we can create...

... detailed computer models of all explored parts of the flooded mine that help us to understand the geology, as well as adding to knowledge of the history of the mining operation!



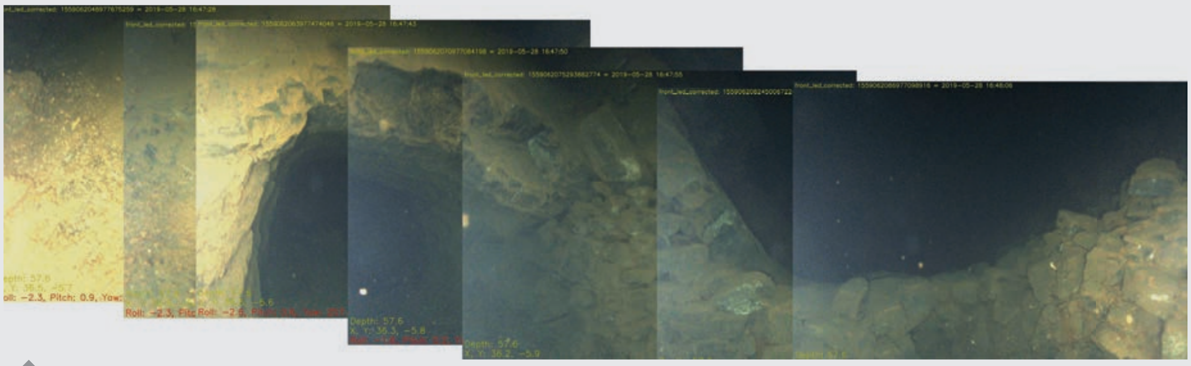
Sonar point-cloud showing Ux-1a in the vastness of a mined-out chamber at Ecton.

Lateral and top views of the point cloud mapping of a vertical shaft. Although the sensors provide raw distance measures resulting in 3D point clouds, these are filtered before registration. For real time navigation the resulting point cloud can be used to incrementally construct fast representation of the environment. This representation divides the environment in occupied and free space cells useful for the navigation process.



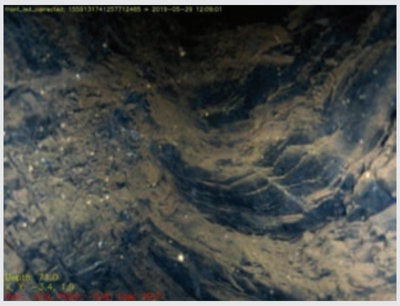
View of a glass block with a 3D engraved model of mine workings.

Data from UNEXMIN's test sites - Some examples of geological features



Composite image showing a cross-cut tunnel at Ecton, from the mined chamber to the winding shaft (left) and downward continuation of the mine workings (right).

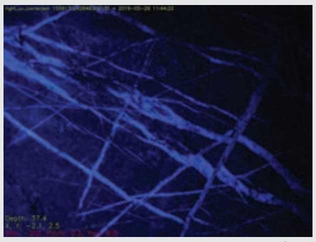
Composite image showing a vertical vein of calcite that runs through 3 meters. The vein is about a centimetre thick.



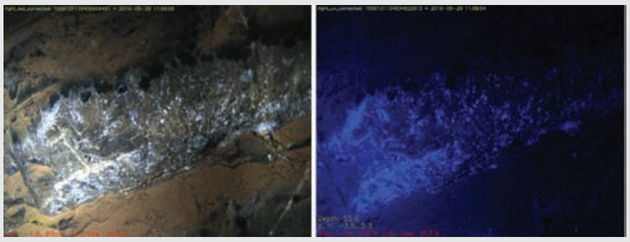
Rounded syncline in thick-bedded limestone.

Edge of worked out pipe with calcite vein and chalcopyrite mineralization in limestone wall rocks.

Multi-phase calcite veining with movement on fracture planes. White LED illumination.



Multi-phase calcite veining. Same area. Ultraviolet illumination.



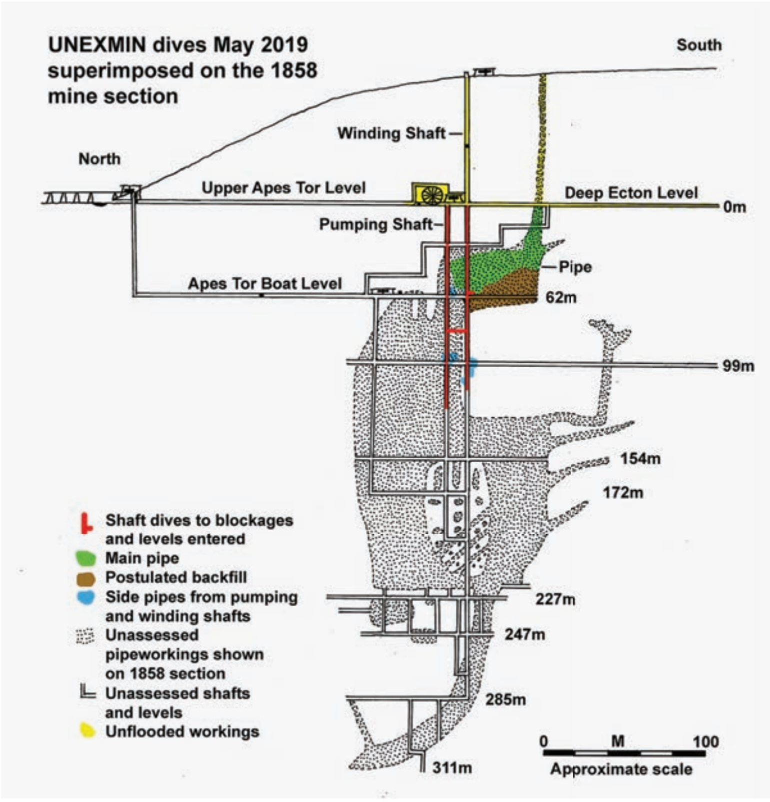
Colour and UV images of a patch of calcite mineralisation in Ecton mine. Calcite is one of the minerals that is easily identified under UV light. Dark nodules may be sphalerite or bitumen but would require more detailed study.

Data from UNEXMIN's test sites - Example of Archaeological feature

At Deep Ecton Mine, which in the 18th century was one of the most important copper mines in Britain, there are large flooded workings that extend down to 300m below river level. These have not been seen since the later 1850s after the mine pumps were turned off. The UNEXMIN dives allowed an exciting opportunity to enter workings not seen for over 160 years.

While the primary aim of the dives was to test the two submersibles, we were also able explore workings for which our prior knowledge was minimal. The most useful source of historical information on where now-flooded features lie is a schematic and over-simplified elevation through the workings dating to 1858.

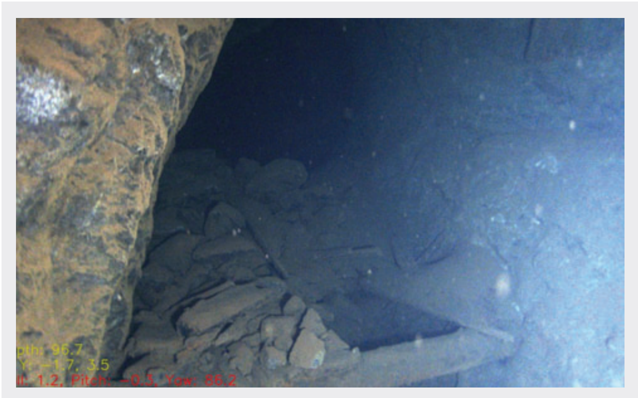
During the ten dives explorations concentrated on the two main shafts and the upper parts of the massive 'pipeworkings' in the mineral deposit. Open leads were left and hopefully these will allow future access to unexplored parts of the flooded workings.



The main pumping shaft was explored to about -125m to a blockage, while the winding shaft was choked at a little under -115m. These are sunk through bedrock, where the bedding was often near-vertical, with many anticlinal and synclinal folds also seen. Both shafts had levels leading off their sides at various depths, some connecting the two shafts, others going elsewhere. In the pumping shaft there were various substantial timbers, thought to be for helping retain the now-removed rods and pipes, the entrances to some of the levels and also ladders. Other features here included three complex groups of mineral workings in 'side pipeworkings' and a 'level' at or just below the underground canal horizon with a walled 'dam' at its entrance.

The approximate extent of passages explored during the UNEXMIN dives undertaken in May 2019 at Deep Ecton Mine, superimposed on the schematic 1858 mine section, with recorded depths of levels (the scale of the 1858 drawing is only approximate as it shows the lower parts of the workings at a slightly larger scale than those parts above).

Launch site at the top of the pumping shaft within the Deep Ecton adit (just above river level).



Opening into the main mine workings - yet to be explored - at 97 metres depth in the winding shaft.

Applicability of the technology

Although the main purpose of this technology was specified as surveying and exploration of flooded underground mines, it has a range of other potential applications. One example is the inspection of underground water reservoirs or water transport tunnels and pipelines, without the need for human divers or the expense of emptying the reservoir. Other potential applications include cave exploration (as demonstrated by the pilot mission in Molnár János cave, Budapest) which may also play a role in cave rescue.

The UNEXMIN technology can be used in a variety of applications and different environments:

- Raw materials exploration
- Water reservoirs surveying
- Cavity measurement (e.g. salt mines)
- Cave system exploration
- Cultural heritage sites investigation
- Environmental monitoring
- Underwater exploration and mining
- Flooded shafts and tunnels of abandoned and operating mines
- Underwater or flooded caves
- Underground river channel systems
- Industrial cooling ponds, lakes
- Other underwater installations / structures that cannot be surveyed by any other means

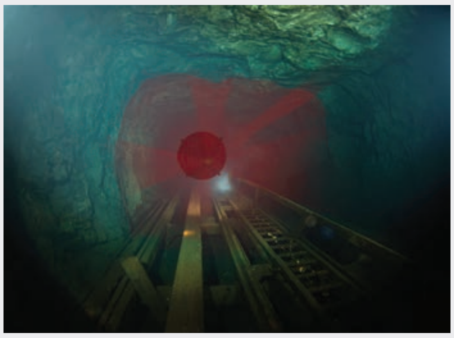
RAW MATERIALS

- Bring information about ores and industrialmineral deposits, opening new exploration scenarios
- Create better drilling exploration plans
- Make improved geological models
- Giving access to new and better geological data necessary to understand Earth's processes and development

CULTURAL HERITAGE

- Provide information about historic evidence of the mine
- Obtain evidence data to complement historical data of a mine
- Supply information about mining artefacts, tools
- Obtain data for reconstruction of mine surveys (galleries, shafts, declines, etc.)
- Obtain data for 3D mine modeling and virtual reality

UNDERWATER ENVIRONMENTS



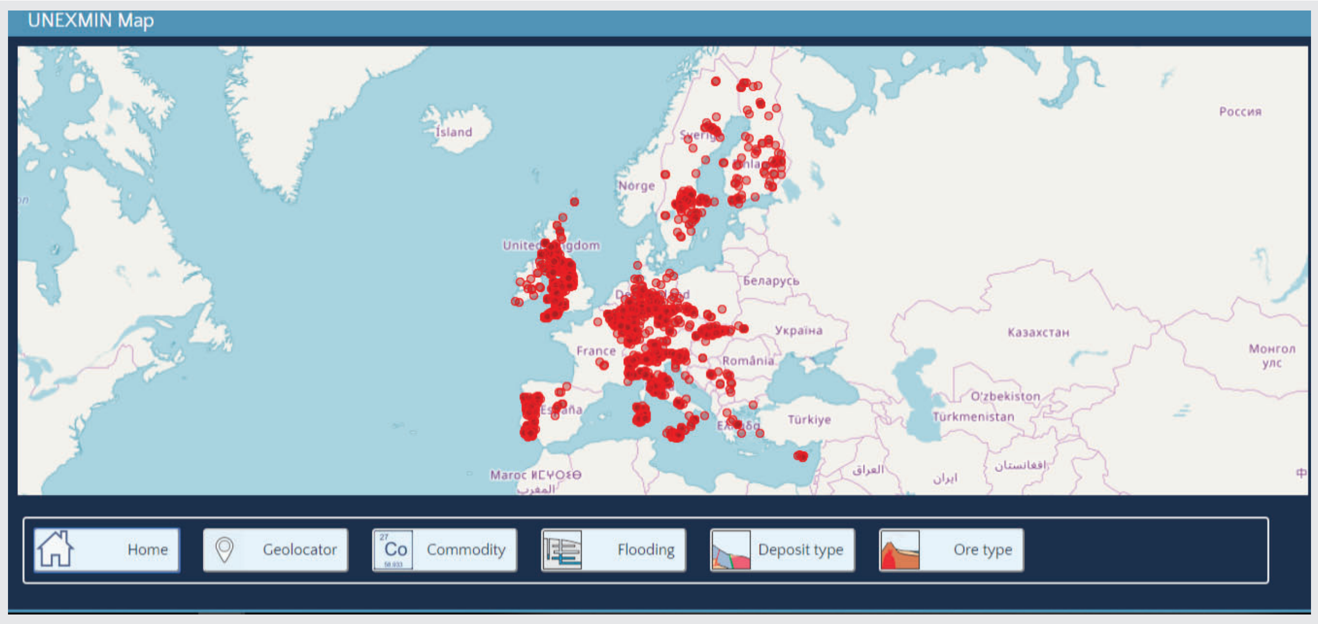
- Identify damage in human-made structures
- Perform risk assessment and rescue missions
- Inspect oil and water pipelines, reservoirs and radioactive waste ponds
- Help manage waste disposal
- Give visual clues on underwater fauna and flora
- Use to salvage commodities from sunken ships and others

Inventory of flooded mines

The UNEXMIN‘s inventory of flooded mines is the first database of its kind and includes data from 24 European countries. The data collection was coordinated by the European Federation of Geologists and involved the Geological Survey of Belgium and 15 national associations. The main target of the research were abandoned underground metallic (CRM) flooded mines. Many of these mines may still contain potentially profitable quantities of raw materials as the main reason for the closure or the abandonment of the mines was economic: the technology and the methods used for mineral extraction were too expensive and it was more convenient to import the necessary raw material from other countries.

The data were retrieved through the review of existing datasets (ProMine, Minerals4EU), desk research and automated approaches (manual data extraction and automated data web-crawling). As the information related to the abandoned mines in Europe is mostly spread among different authorities, associations or publications, the quantity and the quality of the recovered information varies from country to country and from mine to mine. UNEXMIN’s inventory currently covers ~11600 mines from 24 countries and contains information about the mine name(s), its location, its accessibility, the extracted commodities, geological information, the classification of the deposit, the ownership, the activity level, the potential legal restrictions and other useful information. The database is made available via an open-access GIS-based interface and several browsing criteria can be used to extract the relevant information. The user interface is integrated into the UNEXMIN website and is intended to be continued also after the UNEXMIN project.

With the geological information, the deposit classification and data on the last know owner, the UNEXMIN database is a potentially important research tool for the initial estimation and identification of potential sites for future exploitation for critical raw materials. With the development of new mining and refining technologies, mines that were considered no longer exploitable for economic and technical reasons at the time of closure can be reconsidered and re-evaluated in order to reduce the dependency of Europe on the import of raw materials.



The future of the UNEXMIN technology

The next step will be to continue the development of the current technology line, making it more suitable for different types of underwater environments. The UNEXMIN team will pursue new opportunities to develop new instruments, new capabilities and upgrade the current ones. At the same time, UNEXMIN will search new markets and innovative applications for this unique technology.

Some of the highlights of the future UNEXMIN path are:

New and improved capabilities

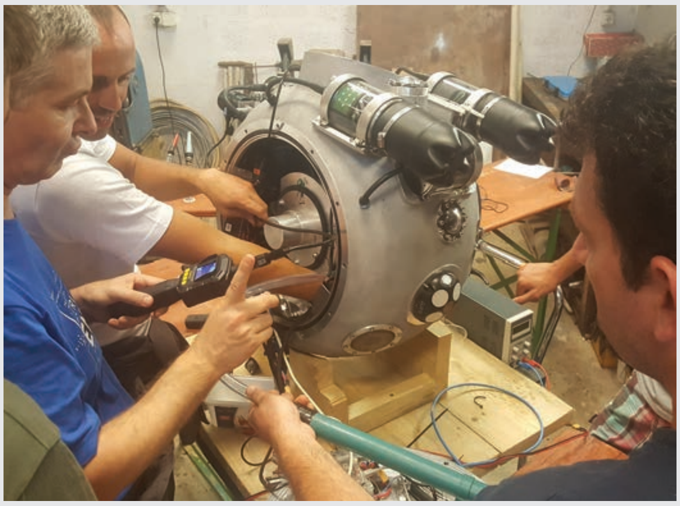
- More autonomy
- In-situ analysis
- Energy harvesting

New and improved instruments

- Rock sampler
- Integrated geophysical instruments
- Higher resolution cameras

Modification to the current UX series

- Different shapes
- Modularity
- Ability to reach deeper



Offering the technology as a service with UNEXMIN GeoRobotics!

UNEXMIN GEOROBOTICS

UNEXMIN GeoRobotics Ltd. is the successor enterprise of the UNEXMIN project.

The multi-robot platform will be commercially exploited as a geological consulting service. The company position itself as a R&D and commercial technology service provider capable of significantly extending the framework for mineral exploration and data acquisition methods, with robotic solutions (initially with underwater surveying) and integration of all available geoscientific data acquired for greenfield or brownfield deep deposits exploration/development, covering land, the continental shelf, ocean floor and other harsh and difficult to access areas.

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Notes

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Idrija Mercury Heritage Management Centre, Slovenia

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