UNEXMIN: a new concept to sustainably obtain geological information from flooded mines

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The UNEXMIN project is developing an autonomous robotic system that can explore and map flooded underground mines, gathering new geological data from locations that are now inaccessible for human exploration and that can be used in future sustainable applications. The robotic system – UX-1 – will have specifically designed tools for the challenging environment. Among these there are the water sampler, magnetic field unit and SLS ("Structured Light Sensor"). In the on-going development phase software and hardware tools for navigation, 3D mapping and data processing are being created. Post-processing software is being developed to provide optical and sonar imaging as well as geochemical, hydrological, geophysical, and mineralogical information from the variety of instrumentation to be carried by UX-1.

Le projet UNEXMIN développe un système robotique autonome qui peut explorer et cartographier les mines souterraines inondées, rassemblant des données géologiques nouvelles, tirées d'endroits qui sont maintenant inaccessibles à l'exploration humaine, et qui peuvent être utilisées pour des applications futures et durables. Le système robotique - UX-1 - comportera des outils de conception spécifique pour faire face aux défis environnementaux. Parmi ceux-ci, on note un échantillonneur d'eau, un capteur de champ magnétique et le SLS (capteur à lumière structurée). Au cours de la phase de développement actuel d'outils de navigation (logiciel et matériel), la cartographie 3D et le traitement de données sont des outils en voie de création. Un logiciel de post-traitement est développé pour fournir des informations de type image optique et sonar tout autant que géochimique, hydrogéologique, géophysique et minéralogique, à partir de la diversité des programmes de mesure qui seront réalisés par UX-1.

El proyecto UNEXMIN está desarrollando un sistema robótico autónomo que puede explorar y mapear minas subterráneas inundadas, recopilando nuevos datos geológicos de lugares que ahora son inaccesibles para la exploración humana y que pueden ser utilizados en futuras aplicaciones sostenibles. El sistema robótico - UX-1 - utilizerá herramientas diseñadas específicamente para este entorno desafiante. Entre otros se encuentran la recogida de muestras de agua, la unidad de campo magnético y el SLS ("Structured Light Sensor", Sensor de Luz Estructurado). En la fase de desarrollo han sido creados, herramientas de software y hardware para la navegación, el mapeo 3D y el procesamiento de datos. Actualmente se está desarrollando un software de postprocesamiento para proporcionar imágenes ópticas y sónicas, así como información geoquímica, hidrológica, geofísica y mineralógica a partir de la variedad de instrumentos que transportará el UX-1.

Concept and approach

UNEXMIN (**Un**derwater **Ex**plorer for Flooded **Min**es) is an EU project funded under the Horizon 2020 Framework Programme that is a direct response to the H2020 Call SC5-11d-2015 on (1) "New sustainable exploration technologies and geomodels", part of an effort for (2) "Ensuring the sustainable supply of non-energy and non-agricultural raw materials", based on the raw materials needs envisaged by the European Commission in recent years. The first topic links to a major challenge identified by the EU: to reduce the dependency on the import of raw materials and solve issues in their entire value chain. Geological uncertainty, technological and economic feasibility of mine development and the growing costs of exploration (including exploration in extreme conditions and challenging environments) are problems for which the EU is actively trying to find a solution. These bottlenecks were first identified by the EIP on Raw Materials (EIP on Raw Materials, 2013). The second link is the aim to improve the knowledge base on raw materials, while also finding "innovative solutions for the cost-effective, resource-efficient and environmentally friendly exploration, extraction, … and recovery of raw materials and for their substitution by economically attractive and environmentally sustainable alternatives with a lower environmental impact" (Programme description, ***http://cordis.europa.eu/programme/rcn/664407_en.html***).

UNEXMIN intends to help solve these problems and it will form the necessary bridge between the geosciences and engineering through robotics development (e.g. with autonomous systems). Bugmann *et al.* (2011) identified many possible roles robotics can play in sustainability: (1) exploration of resources, (2) recycling, (3) reducing waste, (4) enhancing product repairability, (5) monitoring soil, plant and animal conditions and (6) monitoring water contamination, air quality and other environmental measures, among others. UNEXMIN can contribute to several of these aspects: the robotic technology being developed will help in exploring resources in flooded

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mines and other non-easily accessible locations, and can monitor water contamination and other environmental aspects in underwater environments (e.g. temperature, pH). The UNEXMIN project is, thus, connecting geosciences, engineering and sustainability, to be applied to benefit modern society.

In Europe, there are a considerable number of closed mine sites – around 30,000 (ISRM, 2008) and many of these may still contain valuable quantities of mineral raw materials, which usually are minerals that were disregarded during the operational lifetime of the mines due to low commercial value that made their further exploitation economically unfeasible. A classic example of this is fluorite which until recent decades was considered a waste mineral in many lead-zinc mines but is now on the EU list of critical raw materials. With the general increase in prices of most mineral commodities and the huge societal demand presently seen, what was considered unprofitable to exploit decades ago can be regarded today as economically feasible to exploit. With this new vision, the re-opening of closed mine sites in Europe has become a hot topic, with ever-growing interest, as it creates a way to provide a sustainable supply of raw materials and thus reduce the dependence on imports that European industry faces.

A big opportunity for the re-opening of closed mine sites resides in former underground mines: high commodity prices and demand can make their exploitation feasible again. The problem that arises is that the majority of these mines are now flooded, a normal process that occurs when dewatering pumps are switched off after cessation of mining activities, and in most cases information regarding their status and layout has not been preserved, has been lost or was not even prepared.

Knowing what resources are (still) present underground can be the first step for a more sustainable supply and use of mineral raw materials inside the EU, which is one of the EU's major goals for the near future. UNEXMIN will use sustainable methods – environmentally non-invasive and non-damaging – for exploration. By using an autonomous system, like the one being developed, and by following the premise of sustainable exploration, it will be possible to create geomodels for more sustainable exploration scenarios in the future. The novel UNEXMIN technology will perform without the need for using common intrusive exploration methods such as drilling, sampling, tethered equipment or even humans (as divers), that usually have a negative impact on the environment (e.g. damaging nature and the site, using excessive resources such as water and oil, etc.) or can even be considered as dangerous (the risk of losing human lives).

The overall concept and workflow of the UNEXMIN project can be seen in *Figures 1 and 2*, respectively.

Sustainable future applications for the UNEXMIN technology

Although the main objective for the development of UNEXMIN is autonomous exploration and mapping of flooded underground mines, the steps made towards such a novel technology can lead to the emergence of other technologies that can also be applied with sustainable objectives. Particularly, UNEXMIN aims to (1) place the EU at the forefront of sustainable minerals surveying and exploration technologies, (2) provide a better, more efficient solution to evaluate abandoned mines for their mineral potential and (3) offer technology to document and safeguard unique mining heritage that would be otherwise lost or permanently inaccessible.

When fully developed, the technology can potentially be used in a series of sustainable applications in unusual environments that will greatly benefit society, and particularly the geoscience community, in many ways: (1) providing information about min-

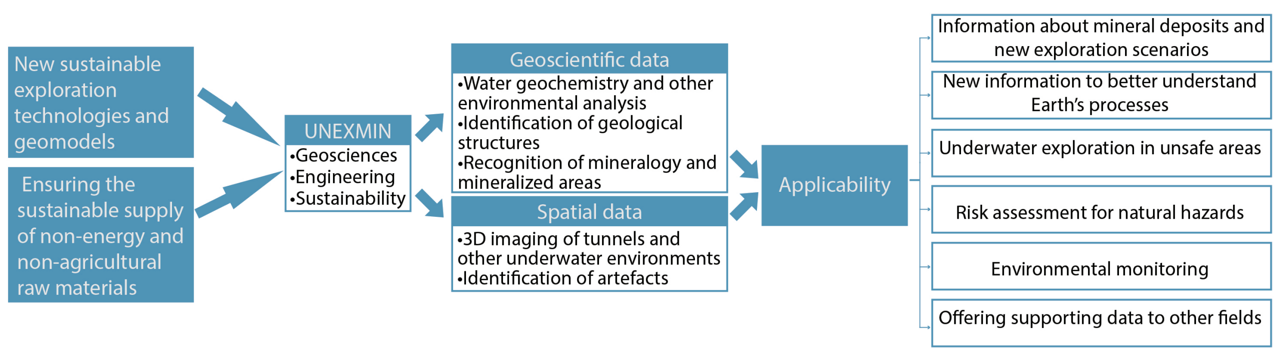

Figure 1: General concept of the UNEXMIN project.

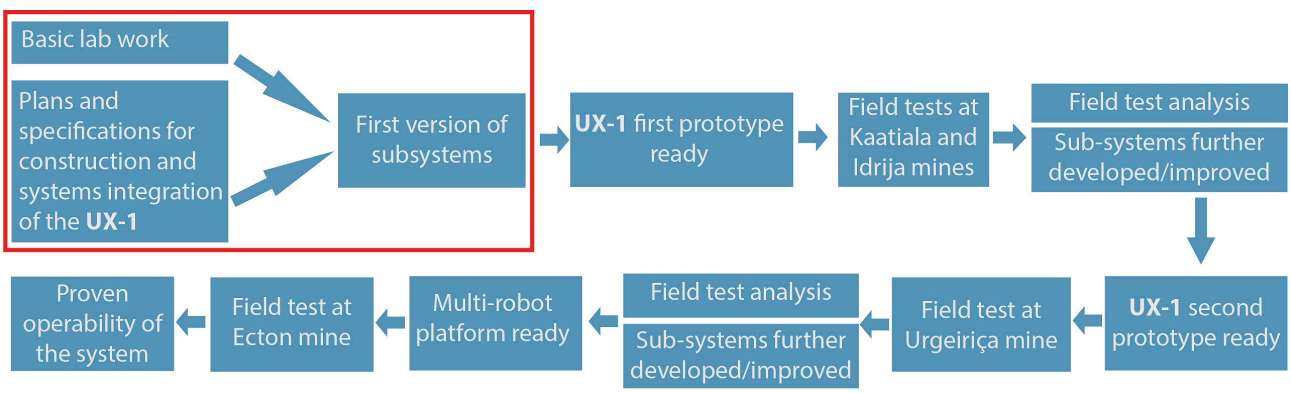

Figure 2: General workflow of the UNEXMIN project.

eral deposits and opening new sustainable exploration scenarios for raw materials, (2) giving access to new, otherwise inaccessible, information necessary to better understand Earth's processes and help to map actions towards a sustainable future, (3) carrying out underwater exploration in unsafe areas (nuclear accidents, toxic spills, surveying of unstable underwater environments – after earthquakes or other catastrophes, etc.), (4) enabling risk assessment of natural hazards (e.g. sinkholes and similar geotechnical problems), (5) environmental monitoring and (6) offering supporting data for fields such as energy efficiency, resource management, archaeology or civil engineering, for instance in the examination and monitoring of underground water reservoirs without the need to drain them.

Development of instrumentation

The surveyor – UX-1 – is designed to employ technologies and equipment derived from state-of-the-art autonomous control and navigation, deep sea robotics and 3D mapping (as a basis). The instrumentation that the robot will carry can be roughly divided into (1) equipment necessary for basic robotic functions such as navigation, control, autonomy or environmental perception and (2) scientific instruments that will generate valuable geological and spatial data. The first group includes thrusters, optical and acoustic cameras, a structured light system (SLS) including laser and white light, pendulum and buoyancy control systems, batteries, a computer and a pressure hull. The second group contains a water sampler, conductivity and pH measuring units, a sub-bottom profiler, a magnetic field measuring unit, UV fluorescence imaging and multispectral imaging units.

The software and hardware tools are being developed, tested and adapted specifically for flooded underground mine environments, where an uncommon combination of conditions must be overcome (e.g. low visibility, confined space, obstacles, water chemistry, etc.). Due to the special environmental characteristics, it is not possible to use methods that require direct contact with the surroundings to collect geoscientific data. Instead, indirect methods will be used such as imaging, geophysical and water sampling methods.

The instruments that are required for some of these methods are described below. Data post-processing is also mentioned, as it is one of the most important processes in geological interpretation.

a) Water sampler unit

A water sampler will collect samples from mine waters and has the final purpose of yielding information about their chemical, biological, radiological and physical characteristics, either through in-situ analysis or a posteriori analysis in accredited laboratories. Some of the most important parameters that can be studied from water analysis are temperature, pH, conductivity (from measurements performed during the missions) and ionic composition (measurements performed after the missions).

The UX-1 unit (***Figure 3***) is designed as a complex storage tank with capacity for 16 different water samples, with each of the samples amounting to 6.8 cm^3. Depending on the pressure, it can take up from 40 seconds to less than 5 seconds to fill a sample task using the power of ambient water pressure. Two independent chambers will be set up in the water sampler: one is the sampling section, filled with sampled water; the other is at atmospheric pressure and contains mainly electrical components and other parts necessary to make the system work, which do not have adequate internal pressure and their own pressure protection.

b) SLS imaging unit

The robot will be equipped with a custom developed set of laser-based structured light systems (SLS) that will provide both 3D morphological information of the scanned environment and imaging (***Figure 3***). Each SLS sensor comprises a laser/light projector unit and a dedicated camera. The camera unit integrates not only the camera itself but also a dedicated embedded processor responsible for the projected laser line detection and triangulation – essential to obtain 3-dimensional data. The laser line projector is mounted in a rotating axis, thus allowing for area sweep even when the robot is motionless. Each image produces a 3D line of points that can then be recorded as a point cloud in the mine's global coordinate system – analysed with post-processing.

The use of multiple SLS sensors in the robot allows the system to be able to simultaneously scan a large volume of its surroundings and thus to build a coherent map of the environment. In an underground flooded environment, this is crucial not only for navigation purposes but also to obtain relevant morphology information on the environment itself.

One relevant characteristic of the sensor is that the LED illumination wavelength can be chosen, and, in particular, different LED wavelengths can be used in different pulses. The UNEXMIN SLS systems have white illumination for standard images and also UV LEDs that can be used to obtain fluorescence images. These indicate the fluorescence properties of some minerals, helping in their identification (e.g. scheelite).

c) Magnetic field measuring unit

The main objective of geomagnetic methods is to explore subsurface geology; they are used in situations such as ground exploration, borehole investigation or aeromagnetic surveys. They are essential to identify magnetic anomalies that can indicate the presence of orebodies or gangue minerals associated with ferromagnetic ore deposits. In UNEXMIN the magnetic field measurements will help to identify possible orebodies, imaging geology and fault structures, or to locate artefacts such as pipes, tanks and other archaeological material of importance inside the flooded mines. Regarding ore bodies, magnetic field measurement

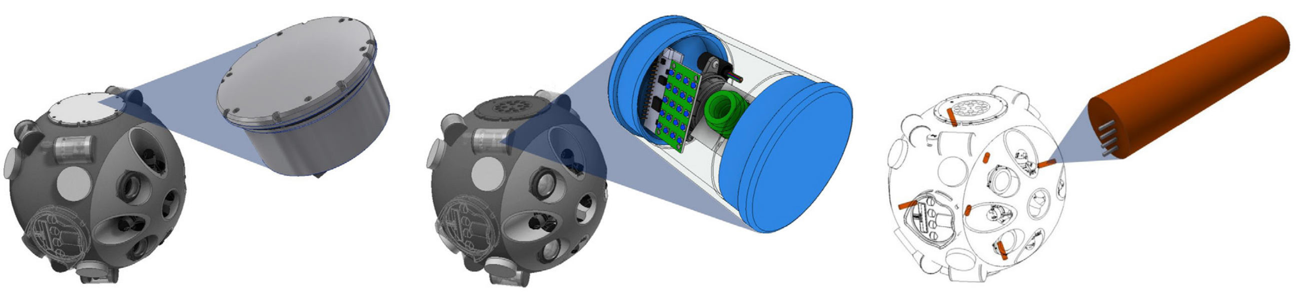

Figure 3: Part of the scientific equipment and their position in UX-1: left – water sampler unit; centre – SLS imaging unit; right – Magnetic field measuring unit.

can help to discriminate massive sulphide bodies – magnetite, hematite, etc. – that usually contain high amounts of commodities (e.g. iron, nickel or copper).

The flux gate sensor system was chosen to measure the magnetic field intensity and direction and is an instrument that collects the data, composed by 6 sensor pieces arranged in three pairs, thus it is three-dimensional sensitive (***Figure 3***). The sensors will be mounted in a perpendicular manner that allows for better measurements of the magnetic field, including very specific local changes. However, it is necessary to compensate the effect of the different electromagnetic equipment built into the UX-1 such as thrusters and cooler fans. Therefore, a compensation process will be applied during data conversion or post-processing to make the data meaningful and valuable.

d) Post-processing software

Post-processing software is used to transform (interpret) the raw data collected by the different instruments into a common database format (e.g. processing of the point-cloud captured by the SLS unit), ultimately allowing creation of usable 3-dimensional geometric and geological models of the flooded mine environments. UX-1 will use miniaturised optical systems to obtain spatial data plus a combination of geophysical and geochemical methods to yield detailed information about environmental parameters (e.g. pH, temperature, conductivity, and concentration of metallic ions of interest in water) as well as multispectral data that will give clues to the composition of the rock faces, and sub-bottom sonar to give an indication of the depth of silt or mud in the mine as well as some clues to the structure of the solid rock below it. Together, it will be possible to identify mineralised areas, which can help in the development of metallogenic models.

Data visualisation will require high-resolution 3D displays supported by fast software algorithms. The data can then be used to learn about the actual status of abandoned underground flooded mines, which could, in turn, support economic assessments for potential re-opening of mining activities. Results from the visualisation software will be presented on computer screens, using virtual reality headsets, and as 3D printed models.

Joint efforts by UNEXMIN partners University of Miskolc and Resources Computing International show that although complex data analysis is needed, it may well be possible to identify or classify wall-rock mineral compositions from the multispectral data. Key software applications for this will include principal components and factor analysis, linear programming optimisation and multiple discriminant analysis.

Field trials

After instrumentation tests in both the laboratory and the field, the UX-1 prototype will be assembled, tested and consequently improved with four trials in flooded underground mines around Europe: the Kaatiala pegmatite mine in Finland, the Idrija mercury mine in Slovenia, the Urgeiriça uranium mine in Portugal and the Ecton copper mine in the UK. The tests will take place from mid-2018 to mid-2019 and will serve as trials in real life conditions, representing increasingly difficult mission objectives in terms of mine layout, geometry and topology. The process will prove the total operability of the system in a set of pilot sites with typical mine characteristics, which can be representative of most flooded mines around Europe. The final and most ambitious trial, to be held in the Ecton underground mine in the UK, aims to resurvey the entire flooded section of the mine, which nobody has seen for over 160 years.

Next steps

The UNEXMIN project is still in its development phase related to the instrumentation, with software and hardware tools for navigation, 3D mapping and data processing being constantly improved and adapted to flooded mine environments. The first UX-1 robotic prototype will be fully functioning and ready by mid-2018 in time for the Kaatiala mine trial. For the period of one year the prototype will be further developed and improved based on the results of the various field tests. In the last test site, in Ecton Mine, we expect to deploy a multi-robotic system formed by three UX-1 robots that will work simultaneously, sharing the workload during their mission.

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