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UNEXMIN: developing an autonomous underwater explorer for flooded mines

Luís Lopes[a,*], Norbert Zajzon[b], Balázs Bodo[a], Stephen Henley[c], Gorazd Žibret[d], Tatjana Dizdarevic[e]

[a]*La Palma Research Centre, Canary islands, Spain*
[b]*Institute of Mineralogy - Geology, University of Miskolc, Miskolc, Hungary*
[c]*Resources Computing International Ltd, Matlock, UK*
[d]*Geological Survey of Slovenia, Ljubljana, Slovenia*
[e]*Idrija Mercury Heritage Management Centre, Idrija, Slovenia*

Abstract

The UNEXMIN project (**Un**derwater **Ex**plorer for Flooded **Min**es) is developing an autonomous multi-platform robotic system that can gather geological data whilst exploring and creating 3D maps of flooded underground mines. In 2017, the project consortium is developing software and hardware for autonomous navigation, 3D mapping, and data post-processing tools. The first of three robotic prototypes will be finished by early 2018. Once construction of this prototype is completed, field trials will commence in four flooded underground mines in Europe. The UNEXMIN multi-platform robotic system will be able to retrieve valuable geological and spatial data that cannot be currently obtained.

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Keywords: flooded mines; robot; mining; exploration; autonomy

* Corresponding author. Tel.: +34 655 191 960
E-mail address: luislopes@lapalmacentre.eu

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1. Introduction

UNEXMIN (Underwater Explorer for Flooded Mines, Grant Agreement No. 690008, www.unexmin.eu) is a European project funded by the European Commission's Horizon 2020 Framework Programme. The project aims to develop a new autonomous multi-platform robotic system, formed by three robots – called UX-1 a, b and c. They will be used for the exploration and mapping of underground flooded mines: these will provide important new geological and spatial data that currently cannot be obtained except by other more expensive or hazardous methods. With the boost in geological knowledge foreseen from UNEXMIN's new technology it will be possible to develop or update geological models at local and regional levels and, ultimately, consider new sustainable exploration scenarios for the re-opening of flooded underground mines. Within the UNEXMIN project, participants will 1) design and build a multi-platform robotic system for autonomous 3D mapping of flooded underground mines, 2) demonstrate the operation of the prototype at a set of representative pilot sites, 3) develop an open-source platform for technology transfer and further development and 4) develop a research roadmap in support of further technology development. This paper intends to give an overview of this ongoing project and its future perspectives.

1.1. Concept and approach

The UNEXMIN project is a response to the European Commission's 2014-2015 Horizon 2020 Societal Challenge 5-11d (SC5-11d) entitled "New sustainable exploration technologies and geomodels" [1]. This competitively funded work detail is part of an effort for "Ensuring the sustainable supply of non-energy and non-agricultural raw materials" in the EU [2]. It intends to lessen the European Union's raw materials import dependency by developing innovative solutions for sustainable exploration scenarios in abandoned flooded mines, while improving the knowledge base for mineral raw materials.

It is known that there are around 30,000 closed mine sites in Europe [3] alone, and a considerable number of these may still have important amounts of mineral raw materials. Many of them were abandoned because low commercial value of the extracted commodity made their further operations economically not feasible. However, prices today are increasing, and the demand has also shifted drastically - what was regarded as contaminant 50-100 years ago, is regarded as commodity today (e.g. fluorite in Pb/Zn mines). Europe has an ever-increasing dependency on the import of raw materials [4,5] and, thus, there is an increased interest in re-opening some of the abandoned mine sites to reduce this reliance. Former underground mines are especially important in this respect, because increased commodity prices and demand could make their operations feasible again. However, the majority of these mines are now flooded and information about their status and layout is in many cases not updated or even lost.

To solve this data gap, UNEXMIN is developing a new robotic system for autonomous mapping of flooded abandoned mines. The system will adapt a wide range of technologies derived from deep sea robotic systems, 3D environment reconstruction, geological laboratory sampling, and autonomous control and navigation. These technologies are being adapted to conditions in flooded underground mines, while integrating imaging and other non-contact[1] surveying technologies and measurement methods that will provide valuable information on the status of these currently inaccessible areas.

1.2. Applicability and expected impacts

By deploying and promoting a novel autonomous robotic system in a new application domain, UNEXMIN hopes to stimulate related robotics technology development for minerals exploration. The project hopes to create an interest in the technology among the raw materials research community, mining industry and cultural heritage assessment parties. In UNEXMIN, it is envisaged to 1) place the European Union in the forefront of sustainable minerals surveying and exploration technologies, 2) provide a high-confidence, low-cost, low-risk solution to

[1] Many flooded abandoned mines are designated heritage sites subject to special protection regimes for archaeological or ecological reasons: this is why non-contact methods are specified

evaluate abandoned mines for their mineral potential and, 3) provide technology to document and safeguard unique mining heritage and/or other long-lost equipment and other artefacts in abandoned mines. When fully developed, the new UNEXMIN technology could be potentially applied for the following (with possible adaptations in the technology depending on the application field):

- Providing information about mineral deposits and opening new exploration scenarios for raw materials;
- Drafting more informed and successful drilling plans for exploration;
- Giving access to new geological data necessary to understand Earth's processes, helping to improve fields within the geosciences;
- Underwater exploration in highly hazardous or dangerous areas (nuclear accidents, toxic spills, surveying of unstable underwater environments - after earthquakes or similar etc.);
- Offering supporting data for areas such as archaeology, civil engineering, energy efficiency or resource management;
- Monitoring the integrity of civil engineering structures;
- Environmental monitoring;
- Cave exploration and tourism planning development.

2. Materials and methods

The work within UNEXMIN started in the beginning of 2016 with the identification of important topics for the proposed technology: 1) limitations in robotic functions and technology associated with flooded mine environments, 2) necessary geoscientific data acquisition and 3) end-user specifications and needs [6]. End-user requirements, as defined by the consortium and external stakeholders, included hull shape and strength, control unit specifications, a propulsion system, navigation and mapping capabilities, sensible robot charge duration, geoscientific measurement instrumentation, maintenance robustness, ease of usability, and reliability [6]. After this initial phase, work focused (and is still ongoing) on 1) validation and simulation of robotic functions, 2) designing, testing and adaptation of instrumentation with great focus on the scientific instrument array, 3) development of mine perception, navigation, 3D mapping and exploration tools and 4) development of post-processing and data analysis tools.Since it is a development of new (beyond state-of-the-art) technology the tasks to reach the final goal will focus on designing, testing and adaption in laboratory and real-life conditions. After this phase – currently ongoing -, the construction of the first robotic prototype will begin. At the same time software and hardware tools will be continuously developed and updated to perfect the submersible. The first robotic prototype is envisaged to be completed in early 2018.

Once the prototypes are ready, the trial phase will begin at the first of four flooded underground mines. In this final stage of the project, extensive submerged expeditions will be arranged. During the testing phase, the robots will be upgraded as they are tested in increasingly complex mine settings. This iterative process intends to demonstrate the platform's scalability from small, low difficulty missions to larger, more complex missions. In the final mission, all three completed UX-1 prototypes will operate as a dispersed autonomous network to map large areas of the flooded underground Ecton mine in England. During this test, real-time sensor and data transmission will enable reliable navigation and communication between robots.

2.1. Test sites

The capabilities of the multi-robotic system will be tested and consequently improved by four trials in flooded mines around Europe: in the Kaatiala pegmatite mine in Finland, in the Urgeiriça uranium mine in Portugal, in the Idrija mercury mine in Slovenia and in the Ecton copper mine in the UK. These tests will occur during 2018 and 2019 and will represent trials in real-life conditions corresponding to increasingly difficult mission objectives in terms of mine layout, geometry and topology. The final test, to be held in the Ecton mine, will deliver the resurveying of its entire flooded section, that nobody has seen for over 150 years. Some characteristics of the flooded test sites in UNEXMIN are described [7].

1. Kaatiala pegmatite mine, Finland

The Kaatiala test will be the first underwater field trial for the UX-1 robotic system. The test location with the mine is a wide horizontal flooded section with no known critical hazards. The purpose of this first test will be to test robotic functions and components in a simple environment so the Project Consortium can modify and fine-tune the technology for more complex trials at the other three mines.

2. Urgeiriça uranium mine, Portugal

The Urgeiriça underground mine was exploited for uranium and radium ores, associated with hydrothermal quartz veins in local granites, between 1913 and 1995. Access to the mine is through a vertical shaft (meaning the robot will have to be deployed vertically from surface). The mining infrastructure comprises 6 vertical shafts and the underground exploitation occurred in galleries 15-30m wide, that extend horizontally for 1600m and that reached a depth of 500m along 18 levels. These galleries are accessible by the main shaft, through a 1x1m wide hatch at the surface.

Table 1. Main characteristics of the Urgeiriça mine

Characteristic	Measure
Maximum depth	580m
Water depth below surface	570m
Maximum shaft length	400m
Maximum gallery length	1600m
Type of obstacles	Possible wood structures and mine galleries collapses
Water quality	pH 6,43; conductivity 705µs/cm; 37 mg/l SO_4; 1,6 mg/l Fe; 4,0 mg/l Mn; 16 mg/l Tss; 0,046 bq/l Ra^{226}; 15,77 ppb U
Important parts to explore in UNEXMIN	Galleries around main shaft

3. Idrija mercury mine, Slovenia

Between 1490 and 1995, the Idrija mine was exploited for hydrothermal ore deposits of cinnabar and native mercury found within sedimentary rocks. Like the Urgeiriça mine, Idrija is accessed through a vertical shaft. Due to the presence of a complex stratigraphic sequence that was geotechnically unfavorable for mine development, there are a substantial number of narrow passages. During its operational life, more than 700km of tunnels were excavated.

Table 2. Main characteristics of the Idrija mine

Characteristic	Measure
Maximum depth	381m
Water depth below surface	192m
Maximum shaft lenght	271m
Maximum gallery lenght	Not relevant; collapsed
Type of obstacles	Possible wood and iron structures and mine galleries collapses. Narrow access passage.
Water quality	7.2 mg/l Fe; 4300 mg/l SO_4, 90 ng/l Hg
Important parts to explore in UNEXMIN	Possible galleries around main shaft

4. Ecton copper mine, UK

The Ecton underground mine, located in the Peak District National Park in the UK (mined principally for copper, but also with important quantities of lead and zinc) was exploited from 1500BC until 1880AD, mainly for chalcopyrite, a copper mineral, hosted in Lower Carboniferous limestone. Mineralisation is hosted mainly in a near-vertical 'pipe' deposit of irregular shape, as well as in steeply dipping veins. Access to the flooded parts of the mine is provided through a horizontal adit at river level (Deep Ecton) or from a level 34m above this (Salts level).

Table 3. Main characteristics of the Ecton mine

Characteristic	Measure
Maximum depth	380m
Water depth below surface	300m
Maximum shaft lenght	300m
Maximum gallery length	Unknown, possibly up to 1km
Type of obstacles	Uneven floors; Wooden structures and wood/iron ladders; narrow workings
Water quality	neutral pH; 10˚ ± 5˚C estimated
Important parts to explore in UNEXMIN	Three flooded shafts and the worked out mineral pipe

3. Results

The flooded underground mine environment constrains basic robotic functions as well as the dimensions and mass of an operable robot. Environmental characteristics restrict both the type and amount of equipment able to be mounted onto each UX-1 robot. In UNEXMIN, the submersible will have the following envisaged characteristics [6]:

- Maximum operation depth of approximately 500m
- Spherical shape
- Diameter of approximately 0.6m
- Expected weight of 112Kg
- Power consumption between 150-300W
- Maximum speed between 1-2Km/h
- Autonomy up to 5 hours
- Thrusters power between 2-5Kgf
- Neutral buoyancy

These attributes derive from a combination of stakeholder desires and needs, the conditions in flooded mines and basic robotic functions required in underwater environments. Considering these three aspects there is a need for a trade-off in the equipment’s quality/quantity/size, considering essential components for basic functions and scientific equipment. Crucial abilities for an underwater robot’s functionality include unobstructed movement, autonomy, mapping and environmental awareness, among others. To enable these critical functions, the robot will employ components such as acoustic cameras, SONAR (Sound Navigation And Ranging), thrusters, laser-scanners, computer, rechargeable batteries, pendulum, buoyancy control system and a protective pressure hull. A schematic layout design of UX-1 is presented in Figure 1.

The UX-1 internal system layout is comprised of several subsystems that will interact among themselves to perform measurement and mobility functions. Those subsystems are: 1) perception system, used to measure environmental conditions and obtain information for navigation and guidance, 2) propulsion system, needed for movement, 3) ballast system, needed for buoyancy control, 4) pendulum, responsible for changes in the pitch angle, 5) power supply system, consisting of five sets of batteries and 6) computer, necessary for the robot’s operation.

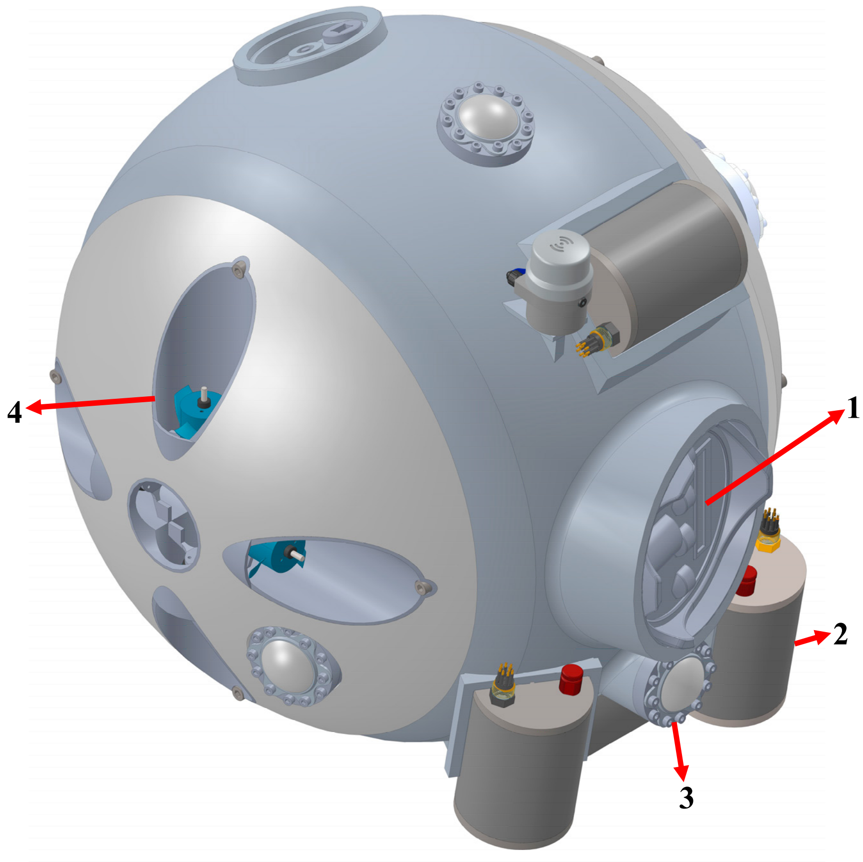

Figure 1: General layout design of UX-1 (3D CAD model): 1 - Multibeam sonar; 2 – Laser scanner; 3 – Camera; 4 – Thruster

To be fully operational, within the concept of UNEXMIN, the robotic system will also need to employ scientific equipment to yield valuable data. Although the best way to generate meaningful geoscientific data is by analyzing mineral samples from the mine walls (direct methods), this is not possible within the UNEXMIN time-frame and budget constraints. The biggest constraints are robotic control (stability), high-precision navigation and positioning, limited power supply and space.

As a work-around for this problem, the robotic system will employ 1) mineralogical (optical) methods, 2) water sampling methods and 3) geophysical methods. Scientific instruments are being designed and built to measure pH, pressure, temperature, conductivity and other geochemical parameters, magnetic fields and gamma radiation levels. An on-board geophysical system will enable sub-bottom profiling, as well as multispectral and UV fluorescence imaging. Water samples within the mine will be collected with a specially designed water tank (Figures 2 and 3). The combination of all of the above-mentioned components will retrieve data on water geochemistry, geophysical imaging and mineralogical identification during UX-1 missions [8-10]. Together with existing information, new, valuable and meaningful geoscientific mine models can be created.

It is important to note that the robot design is still evolving and will continue to evolve during the project lifetime – also with the help from the trials – and that even the smallest changes in one instrument or sensor may enable and/or require changes in other sub-systems.

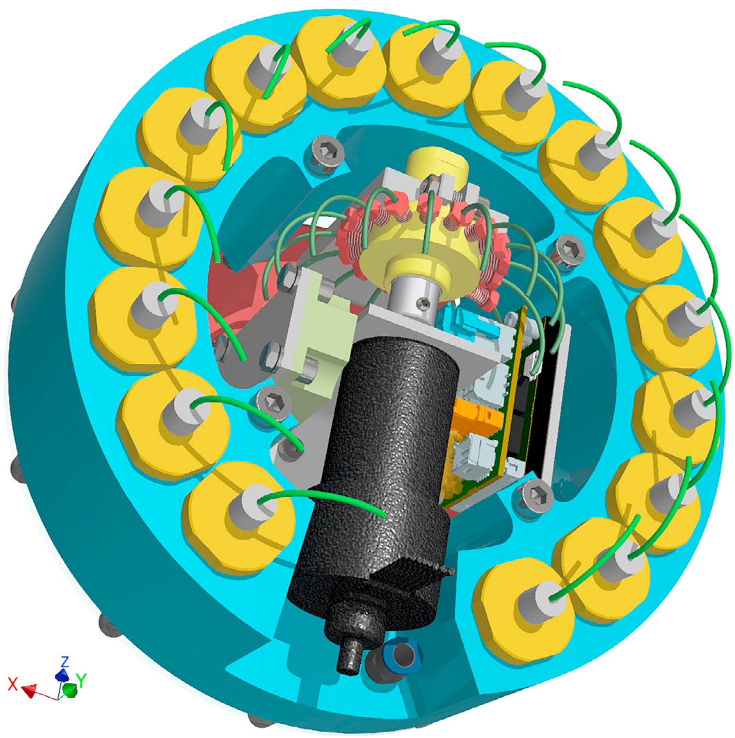

Figure 2: Conceptual design of the water sampler (3D CAD model)

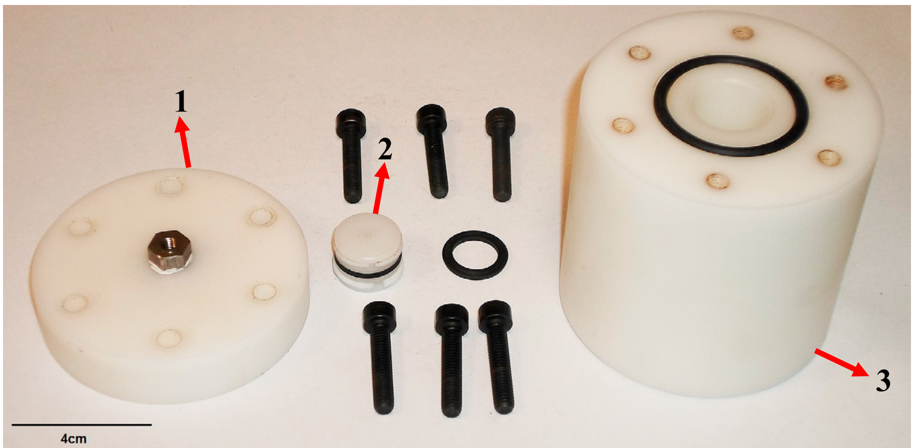

Figure 3: Test water sampling tank and its components: 1 – Closing cover; 2 – Piston; 3 – Sampling tank

4. Discussion

Deploying a multi-robotic system in an environment like the ones usually found in underground flooded mines (low visibility, presence of obstacles, danger of falling rocks and debris, presence of suspended solids in the water, water acidity, difficulties in maneuvering, etc) is very difficult. Research challenges are mostly related to miniaturization and adaptation of deep sea robotic technologies to this new application environment and to the acquisition and interpretation of geoscientific and spatial data. The UNEXMIN team has defined five key challenges that must be addressed for the success of the UX-1 robotic explorer concept:

1. Explorer structural design for robustness and resilience

Physical robustness and self-diagnosis capabilities of the robot can guarantee that it will perform its tasks reliably, safely and with a high level of integrity. The robot needs to be able to fit into small mine openings and to resist high pressures when operating down to a defined depth limit. The structure of the robotic system is being developed to avoid being trapped in narrow dead-ends, to avoid equipment damage and therefore, possible system failures. Measures are being considered to avoid possible failures related to the actuator, battery life or propulsion systems.

2. Localization, navigation and 3D mapping

A feature-based localisation system is being developed by merging multiple sets of relative displacement sensors with global pressure sensors and visual and structured-light sensors. The combination of this equipment means each UX-1 robot will have the positioning, navigation and three-dimensional mapping skills necessary to travel securely around flooded mines to retrieve spatial data.

3. Guidance, propulsion and control

Movement inside mine environments will require buoyancy control, while providing simple control means and reducing external appendages for the robots. Changing the centre of mass, while adopting a pendulum-based angle control, while having lateral thrusters, will contribute to the better movement control of the robotic system in the water.

4. Autonomous operation and supervision

Because of the dense mine walls, physical properties of the water, complex mine layouts and rapid loss of signal strength with distance, it will be impossible to communicate between the human operator and the robot during exploration of the mines. Communication with the submersible explorer will be possible only near the deployment area, using (for example) an acoustic modem. To overcome this problem the robots will have state-of-the-art autonomy functions and will be operating in a multi-robotic platform, made by three UX-1 robots, allowing communication, collaboration and distribution of tasks between the robots.

5. Data processing, interpretation and evaluation

The last of the five key identified challenges, data processing tools must be developed to ensure that the information produced from the surveys are accurate. The 3D reconstruction of the mine workings is, in itself, a major achievement, but the interpretation of the geological information will be a serious scientific challenge. Therefore data processing and visualization tools for geo-scientists and mine engineers are needed.

These challenges, mainly related to the technological development of the robotic system, arise at different points during the project lifetime and are constantly being tackled by the UNEXMIN consortium.

5. Conclusions

The multi-robotic platform developed in the scope of the UNEXMIN project, will provide a big advancement in the field of underwater exploration technology. The first instruments have been developed and tested under laboratory conditions. The development of mine perception, navigation, 3D mapping and exploration tools, as well as post-processing and data analysis tools are the main challenges in this project. The technology developed in

UNEXMIN will be able to retrieve important geological and spatial data that cannot be currently obtained in any other way, data which will have an impact in applications across geosciences, engineering, and resource management. Trials held in four different test sites across Europe will prove the operability of the technology in flooded underground mines' environments.

Acknowledgements

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