UNDERWATER ROBOTICS

SUSTAINABLE EXPLORATION AND EXPLOITATION OF RAW MATERIALS

The need to explore new raw material sites and re-evaluate existing prospecting sites is increasingly becoming a key element for the success of the green transition and for reducing Europe's dependence on raw material imports. The importance of exploring raw material sites is intrinsically associated with the need to optimise the extraction and exploitation of finite resources, mitigating the environmental impact linked to these activities - in which underwater robotics plays a key role, as it is crucial for said harnessing.

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The prospecting and exploitation of underwater minerals has emerged as an important subject over recent years, due to the growing global demand for resources. Over the past decade, we've witnessed a significant global transition towards more sustainable practices and the pursuit of environmentally responsible solutions. This sought-after green transition puts pressure on the supply chain of much-needed raw materials to increase energy production and storage capacity, thereby reducing the use of fossil fuels, and consequently decreasing dependence on non-renewable natural resources. The need to explore new raw material sites and re-evaluate existing prospecting sites is increasingly becoming a key element for the success of the green transition and for reducing Europe's dependence on raw material imports. The importance of exploring raw material sites is intrinsically associated with the need to optimise the extraction and exploitation of finite resources, mitigating the environmental impact linked to these activities - in which underwater robotics plays a key role, as it is crucial for said harnessing.

INESC TEC, in particular the Centre for Robotics and Autonomous Systems, has dedicated more than a decade to underwater robotics, motivated by the search for new knowledge and the ability to study deep-sea and inaccessible flooded areas. Research, development, and innovation play a key role in creating technologies for the identification and exploitation of new raw material sites. The Institute has developed innovative robotic solutions for complex environments and multiple operations, including data collection, inspection, mapping, surveillance, or intervention.

In this sense, INESC TEC has played an active role in several projects related to underwater prospecting and exploitation. INESC TEC was involved in the project ¡VAMOS!, which ended in 2019 and whose main objective was to allow access to European top quality reserves of underwater minerals, providing a novel, safe, and clean mining technique with low environmental impact. In addition, the project has proven the environmental and economic feasibility of harnessing currently inaccessible mineral deposits, encouraging investments and helping to safeguard EU access to strategically important minerals.

The exploration of ore in abandoned and flooded open pit mines was made possible thanks to the development

Figure 1 Photo credits: @Turtle

Figure 2 Photo credits: UX1 Rocky Shore

of a robotic system, composed mainly of an underwater mining vehicle, an Autonomous underwater vehicles to support the operations, and an operations' support vessel. The larger vehicle is a 25-tonne robot equipped with a drilling machine (with the ability to break up rock and pump the extracted material to the surface) on one side, and a hydraulic arm with interchangeable tools on the other. The smaller one, called EVA, moves around the mining site, constantly updating a 3D map of the area and transmitting this cartography data to the larger vehicle, thus improving navigation. The EVA robot was developed entirely by INESC TEC researchers, as well as all sensing, perception, and navigation systems that power an operating environment based on a digital twin. This environment allows the operation of the 25-ton robot in an intuitive and friendly way, like a game.

EVA (Figure 1) is a versatile, multifunctional vehicle that combines high-precision positioning and navigation capabilities with a unique set of observation sensors e.g., 3D multi-beam sonars, cameras, and structured lighting systems for three-dimensional environmental perception with omnidirectional motion capabilities. These features, quite unique considering the robot's dimensions, allow its effective use both in mapping applications during initial surveys, and in the detailed inspection and support to the operation of the mining machine.

INESC TEC has played a major role in this flagship project. But it wasn't the only one, INESC TEC also participated in the European project UNEXMIN.

The UNEXMIN (Autonomous Underwater Explorer for Flooded Mines) focused on the development of underwater robotic systems capable of autonomously exploring and mapping ancient underground mines, without the need for direct human intervention.

There are thousands of abandoned mines in Europe that pose environmental and safety risks but can also contain valuable resources to be recovered. At the time of their decommissioning (in many cases, several decades ago), the technology and interest in high-demand minerals were not the same as today. Therefore, it is urgent to analyse and explore whether the once abandoned mines are likely to be mined again today.

The project involved the creation of three prototype robotic systems for the exploration and autonomous mapping of flooded mines' galleries in Europe. The UX-1 was equipped with advanced cameras, sensors, and navigation systems, allowing it to map the submerged mines and collect data on their condition and economic potential.

During the project, the team carried out tests and exploration missions at several abandoned mines in Europe, including quartz and feldspar mines in Finland, uranium mines in Portugal, mercury mines in Slovenia, and copper mines in the United Kingdom. The underwater robots were able to navigate through the mines' narrow and complex tunnels, collecting geological data, water samples and 3D images.

The first prototype of the UX-1, UX-1a, was developed and assembled in April 2018. During that year, the robot was tested and improved in Kaatiala (Finland, June) and Idrija (Slovenia, September) mines. The second prototype (UX-1b) was built and optimised in March 2019. Both robots were tested in the mines of Urgeiriça (Portugal, March/April), Ecton (United Kingdom, May) and in the Molnár János cave (Budapest-Hungary, June/July).

The results obtained by the UNEXMIN project were quite significant. The exploration missions provided valuable insight into the condition of submerged mines, the presence of mineral resources, and the technical and environmental challenges associated with their retrieval. In addition, the project contributed to the development of advanced robotic technologies and improved our understanding of underground and underwater environments.

The company UGR – UNEXMIN GEOROBOTICS was established because of the UNEXMIN project, with INESC TEC as one the partners, providing mapping and exploration services for mines or other flooded non-oceanic environments.

In addition, a D&I leverage project (upscaling) of the UNEXMIN – UNEXUP concept was accepted for financing in 2020; it focused on increasing the level of operability and robustness of the UX-1 robot by advancing to the development of a product and the provision of services by UGR. This UNEXUP project was completed at the end of 2022 and could not have had better results. The UX-1neo can now navigate up to 500m deep, which is equivalent to 50bar of pressure, while the UX-2deep can operate at 1500m deep. Both feature navigation sensors optimised for state-of-the-art exploration and mapping processes, and they're accessible to anyone through the services provided by UGR.

The increase in global demand for raw materials is not limited to inland mines alone. The possibility of deep-sea underwater mining is also considered. In this sense, it's important to emphasise the relevance of monitoring the impact assessment to ensure sustainable resources' extraction practices. Prior to any type of deep-sea exploration activity, it is crucial to foster competencies to inspect and assess the potential environmental impact of said activities on ecosystems. The European project TRIDENT, launched in 2023 and coordinated by INESC TEC, aims to develop

Figure 3 Autonomous vehicle EVA deployment at sea. (Photo credits: Alfredo Martins)

technologies capable of promoting a significant advance in the assessment of deep-sea environmental impact, in the identification of mitigation solutions, and in the development of new methodologies and operational techniques, while contributing to a solid legal framework (together with the International Seabed Authority – ISA); the goal is to promote the access to the marine mineral deposits in a safe, ecological, industrially viable and socially accepted way.

Besides requiring heavy and expensive logistical support for installation, maintenance, and operation (which limit the effective monitoring capacity), the current monitoring systems for deep-water do not favour the effective network integration for the creation of a real-time monitoring and alerting system.

The TRIDENT project aims to go beyond the current state of the art by bridging existing technological limitations and gaps and establishing advanced methodologies for real-time monitoring of environmental impact and the adoption of mitigation measures in the context of deep-sea mining. TRIDENT will provide a fixed and mobile (modular) wireless network of sensors and autonomous robots that enable real-time environmental monitoring and data transfer from remote deep-sea areas to remote onshore monitoring systems, validated in relevant scenarios (TRL 5). Although the project is still in an initial stage, TRIDENT proves to be promising, and is already considered a flagship project for its ambition and capacity for innovation. The next five years will be challenging for the consortium, but they will certainly be a big step forward in terms of autonomous robotic deep-sea technology.

Most INESC TEC robots are primarily developed to address and solve specific challenges (considering the problems and objectives of the projects that fund them). However, after reaching some functional maturity, the prototypes are quickly integrated into other projects, thus proving the versatility of the technological solutions developed at INESC TEC. The robots previously presented, developed within the scope of projects already completed, are currently being adapted for their use in the open sea, with increased pressure resistance capacity, as well as the ability to withstand currents and environments harsher than controlled environments inside mines.

The EVA robot has been upgraded and developed for open sea operations, with increased autonomy (currently capable of operating up to about seven hours), and movement elements capable of supporting open sea currents. In addition, it has been optimised in terms of resistance to pressure, and it can now reach

Figure 4 UX-1neo operating at the Kőbánya mine in Hungary. (Photo credits: UX1 Rocky Shore)

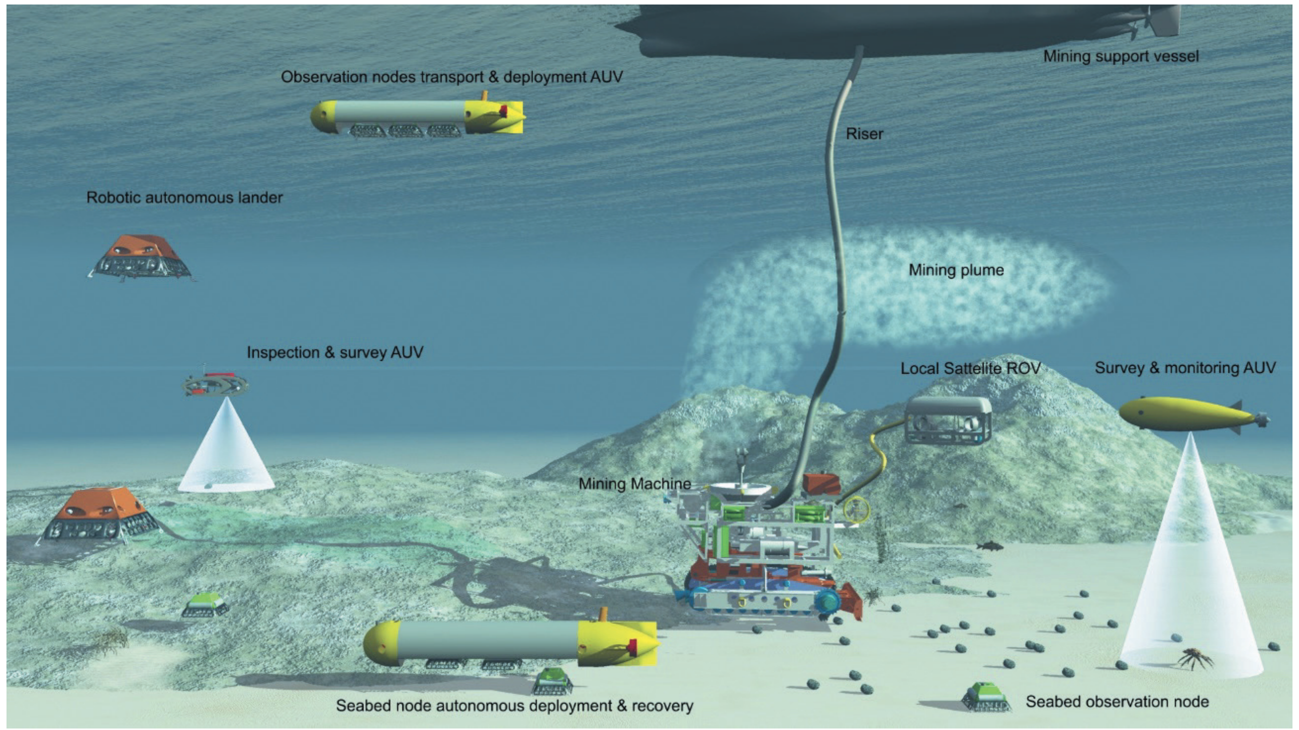

Figure 5 Concept picture of the environmental impact assessment system of deep-sea activities.

depths greater than 1000m - also featuring sensors capable of submerging up to 4000m deep. Recently, it has been equipped with new high-resolution cameras for seabed observation.

The UX-1neo is designed to operate in complex underground environments. However, the applications for this type of system are much more comprehensive. The robotic platform uses non-invasive methods for autonomous 3D mapping of mines, in order to collect essential geological, mineralogical and spatial information. This action can open new exploration scenarios, in which strategic decisions on the reopening of Europe's abandoned mines can be supported by up-to-date data that cannot be obtained in any other way, without great costs and/or risks.

The line of technology employed in the UX1 is only possible thanks to recent scientific advances in autonomy, which allow the development of a completely new class of mining service robots, capable of operating without remote control. Said robots do not exist at the time, with UX-1neo being the first of its kind - having already broken depth records in non-oceanic inland waters, in the Hranice Abyss (Czech Republic).

The main development challenges are related to autonomous operation in complex environments, high accuracy navigation and 3D mapping, miniaturisation and adaptation of open-sea robotics technologies to new applications and environments, and the interpretation of geoscientific data.

The instrumentation carried by the UX1-neo gathers the necessary equipment to obtain valuable geoscientific, spatial, and visual data, while performing basic activities like movement and control.

The UX-1neo's subsystems need to work together to ensure that the robot's features work in any conditions. Together, the sensors, subsystems, and processing/autonomy elements allow the collection of valuable data, which cannot be obtained otherwise. It's also important to emphasise that the use of underwater robots allows operating in flooded mines without the need to remove water from said mines, a task with significant operational costs.

In short, the technological developments of INESC TEC in Underwater Robotics have a great impact on a global scale, with concrete applications in terms of underwater exploration and mining - both in flooded environments on land and in the deep sea. The developments presented always carry an intrinsic societal impact, and they aim to provide a global perspective on the subject, shedding light on the challenges, advancements, and potential benefits associated with underwater mineral prospecting and exploitation, and the monitoring of environmental impact assessment. By understanding the complex dynamics at stake, policymakers, scientists and stakeholders can make informed decisions to mitigate environmental consequences and promote the responsible and sustainable use of these valuable resources.