Autonomous Robotic Exploration in Flooded Mines

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Abstract

Underwater mine exploration is a complex task due to the confined space, the need for high precision and the extreme environmental conditions. Traditional human-based methods are not only risky but also inefficient in submerged environments. This abstract introduces UNEXMIN Georobotics's underwater robotic technology, which provides a safe, non-invasive, and highly efficient alternative to manual exploration, particularly in abandoned, flooded, or hard-to-access mine workings. The introduced robotic system allows us to collect valuable geological and structural data while substantially reducing human exposure to dangerous conditions. This work is important as it addresses the growing need for cost-effective, automated solutions in the mining industry.

This approach is centred around a novel underwater robotic platform designed for confined and extreme environments, specifically tight mine shafts that are often submerged and inaccessible by traditional means (Martins *et al*. 2018). The UX robotic technology incorporates advanced navigation systems, including a Doppler Velocity Log (DVL), inertial measurement units (IMU), multibeam sonar, 360° imaging sonar and high-precision laser modules. The robots are equipped with six cameras and optical cable connection to ensure precise, real-time data acquisition up to 1500 m water depth. What sets this methodology apart is the combination of these technologies in a modular, compact egg-shaped design that can access areas as small as 1 meter in diameter.

The technology's key findings include successful deployments in several test environments and active mine sites, where the introduced robotic system demonstrated its ability to navigate complex underwater environments, collect high-resolution 3D data, and perform tasks autonomously. In 2022, the robot set a world record by reaching 450 meters in depth during a dive in the Hranice Abyss, the world's deepest underwater cave, showcasing its capability to operate in extreme conditions.

The implications of the work done by UNEXMIN georobotics are broad. This technology can be applied to flooded mine exploration, water management in underground environments, geological surveys, and archaeological missions to preserve submerged historical structures. Additionally, it has the potential to substantially shorten the process of reopening flooded mines by providing detailed, real-time data without the need for dewatering or large-scale manual inspections. This technology enhances safety and efficiency. It offers new avenues for industries and governments to explore submerged environments while decreasing the risk and high cost associated with traditional and mostly non-applicable diving methods. As such, UNEXMIN Georobotics' underwater robots represent a breakthrough in the way we approach and manage flooded and confined spaces in mining and beyond.

Keywords: Robotics, underwater, autonomous, mapping, survey

Introduction

Overview of underwater mine exploration requirements

Underwater exploration poses a wide variety of technical and environmental tasks which needs to be addressed, this method is far more complicated than surface or aerial exploration. A principal factor to be resolved is the absence of natural light in deep waters, necessitating the employment of advanced sonar and laser-based mapping technologies. Furthermore, the high pressure encountered in deep environments restricts the utilisation of conventional equipment, thereby necessitating robust robotic systems with pressure resistance as a key attribute. The use of radio signals in water is severely limited, necessitating the development of alternative methods of communication such as optical cables or acoustic signals (Goh *et al*. 2009). The risks posed by flooded mines or underwater cave systems are exacerbated by the confined nature of these environments, which often have narrow passageways that restrict movement and increase the chances of entrapment. The presence of silt and debris as shown in (Fig. 1) can extremely reduce visibility, making navigation highly dependent on advanced sensors and rely more on sonar data instead of visual information to navigate properly.

Another concern is structural instability, as abandoned mines may have collapsed sections or unpredictable water currents that pose additional risks. Furthermore, the absence of standardised maps for many flooded mines means that robotic explorers must rely entirely on real-time data collection to construct navigable models. These difficulties make underwater mine and cave exploration one of the most demanding applications for autonomous robotic systems (Thomas Scott J. C. C. Day and Teague 2017).

The innovative robotic technology developed by UNEXMIN Georobotics Ltd. represents a pioneering approach to underwater mine and cave exploration, facilitating the creation of geo-referenced, highly accurate 3D maps. This capability is of considerable importance for several reasons. Firstly, flooded mines and underwater cave systems frequently lack existing maps or possess outdated and imprecise records due to structural collapses and sediment shifts over time. The employment of an autonomous underwater robot has the potential to facilitate non-invasive exploration of cave systems, a task that is of considerable scientific value. The unique adaptations exhibited by cave organisms to low food availability, hypoxic waters and darkness, make them a subject of particular interest.

The deployment of a robot equipped with cameras and sensors could assist in the documentation of biodiversity, the monitoring of population distributions and the collection of environmental data, without causing disturbance to fragile ecosystems (Pérez-Moreno *et al*. 2017). Utilising advanced navigation systems, including Doppler Velocity Logs (DVL), inertial measurement units (IMU), and multibeam sonar, UNEXMIN's robotic solution can generate detailed spatial models that provide a clear and up-to-date representation of these treacherous environments. In addition to mapping, the robotic system is capable of collecting critical environmental data, such as salinity, pH levels, and oxygen concentration. These parameters are critical for comprehending the geochemical conditions of submerged sites, which in turn influences decisions related to mine reopening, water management, and preservation efforts. For instance, measuring oxygen levels can assist in evaluating the potential for microbial activity that might lead to structural degradation, while pH and salinity data provide insight into corrosion risks for existing infrastructure. The integration of these environmental factors into a geo-referenced model, facilitated by this technology, has the potential to enhance exploration, as well as to provide informed decision-making support to industries, researchers and policymakers in the domains of resource management, safety and conservation of these hidden underwater worlds.

Importance of autonomous robotic solutions

The deployment of robots for the purpose of underwater mine and cave exploration offers outstanding advantages over traditional

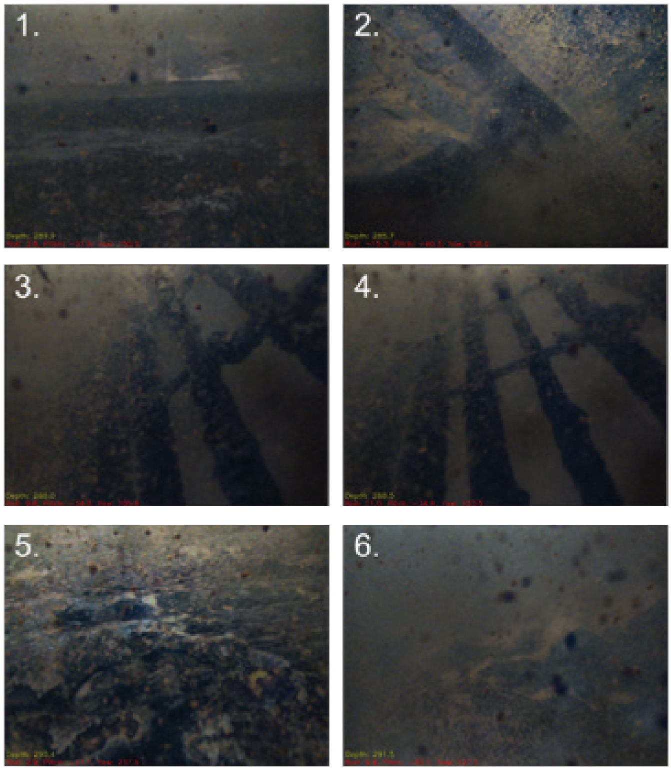

Figure 1 *Low visibility during a dive caused by murky water and sediments.*

human-based methods, primarily in terms of safety, efficiency, and data quality. A primary benefit is the elimination of human risk. Flooded mines and underwater caves present life-threatening conditions, including structural instability, low visibility, strong currents, and extreme pressure. By using autonomous or remotely operated robots, human divers are not exposed to these hazards, reducing the likelihood of accidents and fatalities (Courtenay *et al.* 2012).

Furthermore, the deployment of robots ensures unparalleled efficiency in exploring such environments. In contrast to human divers, who are limited in endurance and require extensive support systems, robotic systems possess the capacity to operate continuously for extended periods, thereby enabling the collection of high-resolution data without the necessity of decompression stops or breaks and of course to risk human life (Mcleod and Jacobson 2011). The integration of advanced sonar, laser scanning, and imaging technologies enables the generation of precise 3D maps of submerged structures, thereby facilitating insights that would be almost impossible to obtain manually. Furthermore, the ability of robots to access areas that are too tight, deep, or hazardous for divers is a notable advantage, rendering them indispensable for investigating abandoned mines, collapsed tunnels, or unknown cave systems. Their autonomy, capacity to adapt to unexpected obstacles, and the ability to relay real-time data make them a highly effective tool for exploring and managing underwater environments.

The robotic platform

Navigation and mapping

Sonar, an acronym for Sound Navigation and Ranging, is a technique that uses sound waves to detect and locate objects underwater. Initially, a sonar system emits sound waves, typically in the form of short pulses or continuous waves, through a transducer. The transducer serves to convert electrical energy into acoustic energy, thereby transmitting the sound waves into the water (Gray *et al*. 2019).

The sound waves travel through the water until they encounter an object, such as the seabed, a submerged structure, or marine life. The speed of sound in water is faster than in air, typically around 1 500 m/s. When the sound waves hit an object, they are reflected toward the source. The sonar system incorporates a receiving transducer that detects these returning sound waves, known as echoes. The echoes are then processed by the sonar system to create a visual representation of the underwater environment, including the determination of water depth, location of objects and identification of their shapes and sizes based on the strength and timing of the echoes.

The employment of advanced sonar systems, such as multibeam sonar, facilitates the emission of multiple sound beams concurrently, thereby ensuring comprehensive coverage of a vast area and enabling precise mapping of the seafloor and submerged objects. 360° imaging sonar, on the other hand, provides real-time visualisation of the surroundings by generating a comprehensive image of the underwater environment. Sonar technology finds extensive application in diverse fields, including underwater exploration, navigation, fishing, and search and rescue operations. Its value is particularly evident in environments where visibility is limited, such as turbid waters or deep-sea conditions, where it is indispensable for marine research and exploration.

In the context of underwater mine exploration, a considerable technological problem arises from the absence of GPS signals, thereby rendering these environments GPS-denied. To navigate and map such areas, the robotic system relies on a manually marked location provided by geologists, who base their information on accurate GPS data obtained from the surface. To effectively operate in these conditions, the robotic system utilises a combination of advanced technologies. To create detailed 3D models of the environment, the system employs a structured light system and sonar technology. The functioning of the structured light system is based upon the projection of a known pattern of light onto surfaces, with the subsequent capture of the resulting deformations by means of cameras. The analysis of these deformations enables the system to construct high-resolution 3D representations of submerged mine structures. Furthermore, sonar technology is used for the detection and location of objects underwater. The robot is equipped with a multibeam sonar, which emits multiple sound beams to cover a wide area, and a 360° scanning sonar, providing real-time visualisation of the surroundings for obstacle avoidance. Together, these technologies enable the robot to create accurate and detailed 3D maps of the underwater environment (Franchi *et al*. 2021).

Accurate positioning and navigation in GPS-denied environments rely on the Doppler Velocity Log (DVL) and a highly precise Inertial Measurement Unit (IMU). The DVL is a sonar-based instrument that measures the robot's velocity relative to the seabed or water column by emitting acoustic signals and analysing the Doppler shift of the returned echoes. The data gathered from this process is then integrated over time to estimate the robot's position using a method known as dead reckoning, which is critical in the absence of GPS. Simultaneously, the IMU provides highly precise measurements of the robot's orientation, acceleration, and angular velocity, information which is fundamental for maintaining a stable course and correcting any drift, thereby ensuring reliable navigation and positioning. The integration of a structured light system and sonar technology for 3D modelling with the DVL and IMU for accurate positioning and navigation enables the robotic solution to effectively explore and map environmentally testing underwater locations, such as those without GPS, ensuring safe and efficient exploration of previously inaccessible areas (Kok *et al*. 2017).

Instrumentation

The technology facilitates the deployment of multiple sensors, enabling in-situ analysis of mine water. This analysis is imperative for the monitoring and management of the environmental impact of mining activities. The sensors employed include a pH meter, an oxygen concentration meter, a temperature sensor, and a conductivity sensor and there is also a possibility for hyperspectral imaging. pH is a principal parameter in evaluating water quality, as it influences the solubility and bioavailability of nutrients and contaminants. For instance, acidic waters have been observed to leach harmful metals from mine waste, while alkaline waters have been found to indicate the presence of certain minerals. Monitoring pH levels is, therefore, a key aspect of environmental risk identification and ensuring that water quality remains within acceptable limits for aquatic life (Nordstrom 2011). The oxygen concentration meter measures the amount of dissolved oxygen in the water. In mining operations, the presence of pollutants can deplete oxygen levels, so monitoring this parameter helps assess the health of the aquatic ecosystem and the impact of mining activities. The robot is also equipped with a high precision temperature sensor that can measure water temperature with an accuracy of ±0.1 °C. The conductivity sensor quantifies the electrical conductivity of water, which is directly proportional to the concentration of dissolved ions. Elevated conductivity levels may be indicative of high salt or pollutant concentrations, which can result from mining operations. Conductivity monitoring facilitates the assessment of water quality and the identification of potential contamination. In-situ mine water analysis using these methods is imperative for several reasons. Primarily, it enables real-time monitoring of water quality, facilitating timely responses to potential environmental issues. Secondly, understanding the chemical and physical properties of mine water is essential for assessing its impact on local ecosystems and ensuring compliance with environmental regulations. By utilising these sensors, the robot contributes to a comprehensive understanding of the water quality in and around mining sites, supporting sustainable mining practices.

Hyperspectral imaging represents a sophisticated technological advancement that facilitates the acquisition and analysis of a broad spectrum of wavelengths across the electromagnetic spectrum. In contradistinction to conventional cameras, which are limited to the capture of images in three primary colours (red, green, and blue), hyperspectral imaging employs the collection of data across a multitude of contiguous spectral bands, thereby enabling comprehensive analysis of the materials present in the environment (Zawada 2003). The operational principle of this technology entails the utilisation of a specialised sensor to capture light reflected from surfaces in the form of a spectrum. The unique spectral signature of each material is characterised by its specific pattern of reflectance at different wavelengths (Tschannerl *et al.* 2019). By comparing these spectral signatures to those of known reference materials, the system can identify the composition and characteristics of the observed materials (De La Rosa *et al.* 2021). In the context of identifying mineralisation, hyperspectral imaging is particularly valuable. When the robot surveys an area, it can detect various minerals based on their spectral signatures. For instance, distinct reflectance patterns are exhibited by minerals such as silicates, carbonates, and oxides, which can be identified through hyperspectral analysis. This capability enables the robot to map and characterize mineral deposits with a high degree of precision.

Results

A 3D point cloud generated by the robotic system, illustrates the spatial configuration of a mine (Fig. 2). The dataset clearly shows a decline leading to two horizontal tunnels and a smaller chamber. The colour gradient in the point cloud clearly shows elevation variations, with the transition from red to blue indicating depth changes. This visualization supports precise geospatial mapping, aiding in the navigation of autonomous systems and facilitating further geological or mineralogical studies within the mine.

As described, with the help of the robotic platform, photogrammetric models also could be generated (Fig. 3). The model accurately depicts the geological features of the tunnel walls, revealing fine details such as miner-inscribed markings, structural

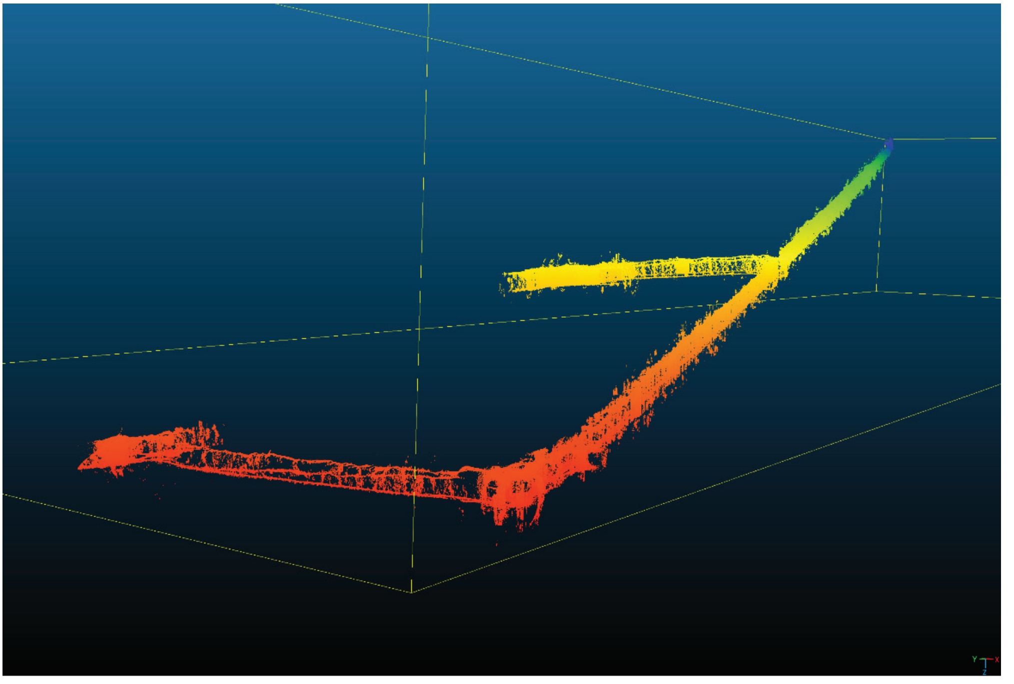

Figure 2 *3D point cloud of an underwater mine section.*

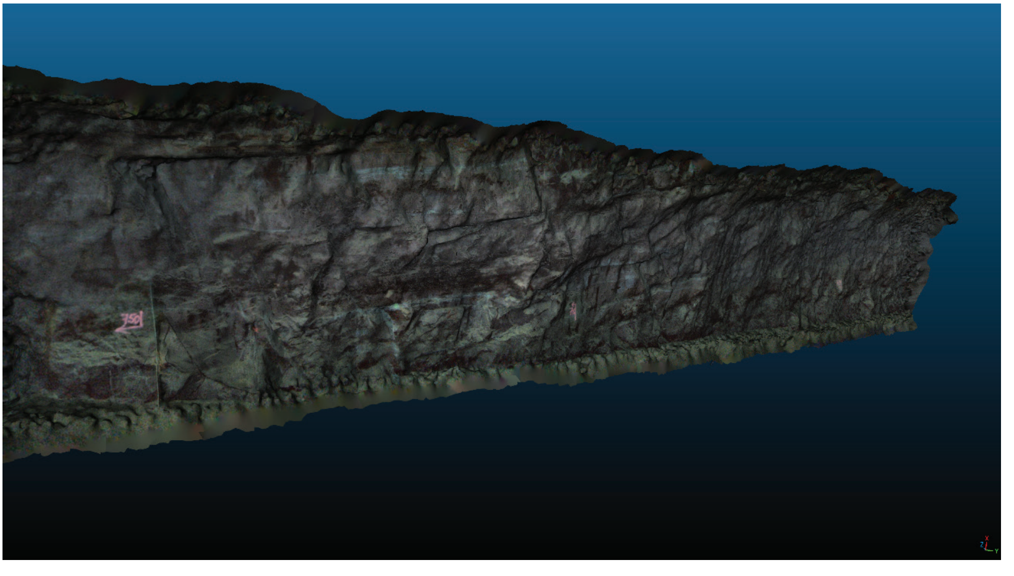

Figure 3 *3D Photogrammetric model of a mine decline.*

discontinuities, and surface textures. This high-fidelity representation facilitates a multifaceted analysis, including geological analysis, structural integrity assessments, and historical documentation of submerged mining environments.

Conclusion and prospective developments

At present, a major focus of development at UNEXMIN Georobotics Ltd. is to increase the level of autonomy for its robotic systems. Efforts are being made to enhance onboard decision-making capabilities using machine learning algorithms that enable the robot to assess its surroundings, navigate obstacles, and adjust its course dynamically without external input. The integration of advanced sensors and automated pattern recognition aims to minimise the necessity for remote human intervention, thereby enabling robots to execute missions autonomously, even in highly unpredictable environments. This enhancement is expected to markedly boost operational efficiency, rendering underwater exploration safer and more effective by empowering robots to adapt to unforeseen scenarios in real time. Also, the team is working towards to set a new world record by exploring the depths of the Hranice Abyss, the world's deepest known underwater cave, with the aim of reaching an unprecedented depth of 1,500 metres in a natural freshwater cave. This mission is not only seeking to set a new world record, but also to collect valuable geological and environmental data, thereby facilitating a more profound understanding of the cave system's structure and conditions. The insights gained from this exploration will contribute to scientific knowledge and advance the capabilities of autonomous underwater robotics in extreme environments.

UNEXMIN Georobotics Ltd has already developed advanced robotic solutions that have been adopted by gratified commercial clients in the mining sector. The company is now seeking to establish new partnerships with organisations in the mining industry with a view to exploring abandoned mines and conducting detailed underwater surveys. The aim of these collaborations is to provide cost-effective and highly precise assessments of flooded or hard-to-reach mining sites. These partnerships will enable safer, faster, and more efficient decision-making regarding mine reactivation, resource estimation, and hazard identification. The company's ongoing dedication to innovation and strategic collaborations is integral to its mission of shaping the future of autonomous exploration, while concurrently providing the mining industry with state-of-the-art technological solutions.

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