The ¡VAMOS! Sustainable Underwater Mining Solution

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¡VAMOS! – Viable Alternative Mine Operating System – is a research project funded by the H2020 program which is building a prototype underwater mining system that will provide a novel way of exploiting inaccessible inland mineral resources that lie beneath the water table. The project is developing a submerged remotely controlled mining vehicle prototype with associated launch, recovery and ore collecting equipment. The system is also equipped with cutting-edge technology for environmental data collection and real-time grade control. The ¡VAMOS! technology is expected to provide major advantages in the fields of environmental sustainability and safety with respect to conventional mining methods. Two separate field trials will prove the environmental integrity and economic viability of the concept.

¡VAMOS! (Système d'opération minière alternative, viable) est un projet européen de recherche, de création commune, sous forme d'un prototype de système d'exploitation minière sous marine qui procurera un nouveau moyen d'exploitation des ressources minières continentales, présentes en-dessous du niveau statique. Le projet développe un prototype de véhicule minier immergé, avec contrôle distant, démarrage associé, équipement de récupération et de collecte du minerai. Le système est également équipé d'une technologie en pointe pour la saisie des données environnementales et le contrôle de leur qualité en temps réel. On attend de la technologie VAMOS, des avancées majeures dans les domaines de l'environnement durable et de la sécurité, tout en respectant les méthodes minières conventionnelles. Deux expérimentations séparées vont attester de l'intégrité environnementale et de la viabilité économique de ce concept.

¡VAMOS! – Viable Alternative Mine Operating System – es un proyecto de investigación financiado conjuntamente por la Unión Europea que está construyendo un prototipo de sistema de minería submarina que proporcionará una forma novedosa de explotar los recursos minerales inaccesibles, ubicados debajo del nivel freático. El proyecto está desarrollando un prototipo de vehículo de minería sumergido, controlado a distancia, con equipamiento asociado al lanzamiento, a la recuperación y a la recolección de minerales. El sistema también está equipado con tecnología puntera para la recopilación de datos ambientales y el control de posición en tiempo real. Se espera que la tecnología de ¡VAMOS! brinde mayores ventajas en los campos de sostenibilidad ambiental y de seguridad con respecto a los métodos de minería convencionales. Dos ensayos de campo separados demostrarán la integridad ambiental y la viabilidad económica del concepto.

Introduction

Europe is highly dependent on imports of raw materials that are needed to support its industries. Securing a reliable supply of minerals that are essential for the European quality of living and economy has been a top priority for the EU in the past years (European Commission, 2017). Mineral raw materials have been mined over many centuries in Europe. However, many mines that have been closed because they could not be economically operated in the past still contain valuable raw materials. Modern mining and processing techniques make mining of previously uneconomic deposits possible today, since the economically exploitable average grade of present-day operating mines has continuously decreased over time. Many mineral deposits in Europe are also submerged, either through flooding of mines after they were abandoned or in unmined deposits that lie below the water table.

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¡VAMOS! is developing a new mine operating system that allows minerals to be extracted in an underwater open-pit environment. The ¡VAMOS! mining technique will enable re-opening of these abandoned open-pit mines, extend the lifetime of opencast mines which are limited by stripping ratio or hydrological and geotechnical issues, and will allow the opening of new mines with limited environmental impacts in the EU. The ¡VAMOS! solution was developed in response to a Horizon 2020 Research and Innovation call for 'New solutions for sustainable production of raw materials' by 17 partners from 10 European countries.

The ¡VAMOS! mining technology

The ¡VAMOS! system consists of several components (***Figure 1***). A remotely-controlled underwater mining vehicle is equipped with a cutter-head that will cut rocks to fragments of about 50 mm. The resulting mined material will be fed into a dredge suction mouth by a rotating auger, and a grill over the suction mouth will prevent blockage of the piping by large rock fragments. The mined slurry will be pumped up to the surface through a riser to an anchored launch and recovery vessel (LARV) and then through a hose system to an on-land dewatering facility, where the mined material will be separated from water before further processing and the excess water will be returned to the mine pit. The LARV also serves to launch and recover the mining vehicle from the water and provides the surface link for the communications and

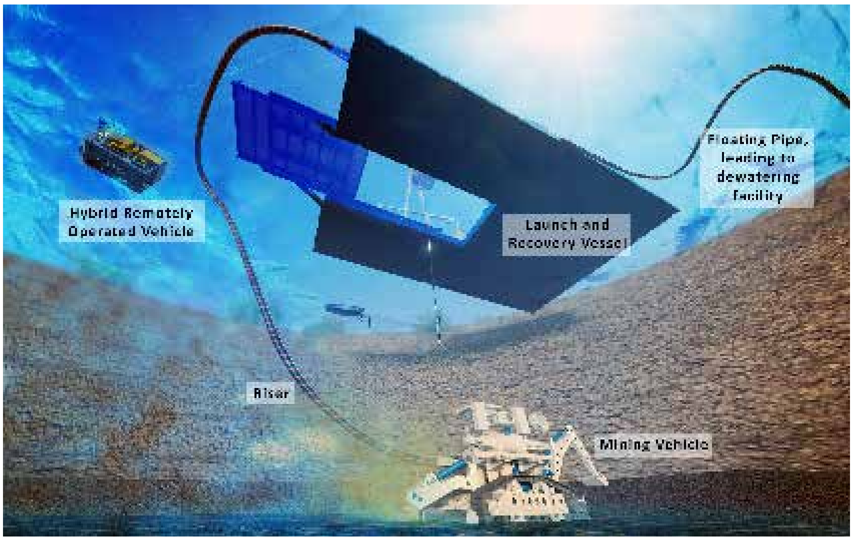

Figure 1: Artist's impression of the ¡VAMOS! technology in action (Damen Dredging).

power tether. The entire system will run on electricity, which can be provided by diesel generators or from the electrical grid.

The exact positioning and navigation of the mining vehicle and situational awareness of its environment will be accomplished with a tether-less hybrid remotely operated autonomous underwater vehicle (HROV/AUV) that will operate in parallel with the mining vehicle. It will collect visual and sonar information for situation modelling, obstacle avoidance data and vehicle positioning and orientation data.

The mining machine positioning is obtained by a localisation solution that fuses Short Base Line acoustic positioning (with a set of transponders fixed on the LARV) with an on-board inertial motion unit providing orientation information. Assisted by this data, all machinery can be controlled and operated via a 3D virtual reality human-machine interface onshore.

In addition, the mining vehicle also carries a set of sensors providing situational awareness, which allows safe and efficient remote operation. The sensors consist of a multibeam sonar system and an underwater camera (and lights) mounted on a pan-tilt unit, on several cameras and lights located at relevant machine points and in a set of custom developed laser-based structured light systems (SLS). These systems provide not only standard visual information, but also, when the water turbidity conditions allow, 3D point cloud measurements of the environment. This 3D information together with the range data from the sonar is fed into the mine map that is produced in real-time and used in the virtual reality environment.

The autonomous underwater vehicle is also equipped with a multibeam sonar and set of SLS sensors to gather precision 3D environment information. Its positioning is obtained with the aid of an inverted (Ultra) Short Baseline acoustic solution and on-board inertial navigation sensors. An acoustic communications link is established with the surface for low rate telemetry and teleprogramming. In addition, a custom developed short range underwater electromagnetic communication system is used for direct teleoperation when required (and within range) and for high bandwidth information transfer (such as images or sonar data).

The HROV is used in different stages of the mining operation. Initially it surveys the mine pit and produces an initial bathymetric map that can be used in the mine planning operations. During mining operations, the HROV is used both for gathering 3D data and updating the map and for additional situational awareness, providing a freely controllable viewpoint for the operations.

The mining vehicle will also be equipped with laser induced breakdown spectroscopy (LIBS) for real-time grade control. This system is attached to a small diversion on the slurry circuit and produces a high rate set of spectroscopy measurements of the slurry. These are correlated with pre-existing calibrated responses from the minerals expected to be present at particular location allowing real-time ore grade monitoring and obtaining of production statistics. This allows for more efficient mining operation and reduces the cutting of waste.

Application and expected environmental sustainability

Because the ¡VAMOS! technology is completely new and has yet to be field tested (as of September 2017), scientific data is still required to confirm the best application domain and the potential environmental impacts. It is also crucial to answer the question where exactly iVAMOS! technology is a more cost-effective extraction method in comparison to conventional in-land mining. One of the major economic advantages of the technology is that groundwater does not need to be pumped out of the mine continuously. The resulting lower energy consumption is not only more cost efficient, but will lower the carbon footprint of the operation as well. Another big environmental advantage is that the local water table will not be affected, limiting the effects of the mining operation on surrounding hydrological systems, vegetation, and ecosystems. Considering that the extraction will be located underwater, there will be no significant noise or dust emissions, and due to hydrostatic effects less energy will be required to transport ore to the surface. It is also expected that ¡VAMOS! technology will allow lower stripping ratio, since sidewalls are expected to be more stable underwater than in dry conditions (***Figure 2***). The reasons for this are that there will be no blast over-break, ground

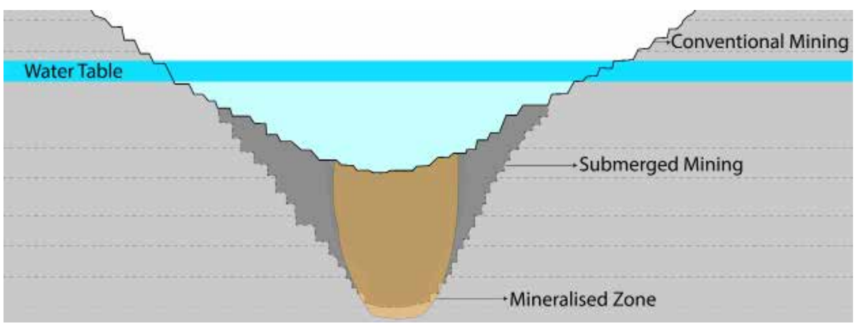

Figure 2: Sketch of a conventional opencast mining operation, requiring dewatering and the removal of large volumes of waste rock, compared to submerged mining with a lower stripping ratio due to more stable sidewalls in hydrostatic conditions.

Table 1: Comparison of key components of mining in open-pits, off-shore and in the ¡VAMOS! concept according to their economic importance.

Economic factor	***Conventional in-land open-pit mining***	***Off-shore mining***	***¡VAMOS! concept***
Dewatering	*Related to climate and depth of operation, risk of flooding; it is often the limitation factor for further development of mine*	*No need for dewatering*	*No need for dewatering, pit semi-immune to flooding*
Crushing	*Depending on the ore hardness and extraction type; generally after blasting ore is transported and crushed in primary and secondary ore crushers*	*Ore is primarily crushed during extraction*	*Ore is primarily crushed during extraction*
Productivity	*Depending on the extraction technology; open-pit mining allows very large operations*	*Limited by size and quantity of the machinery*	*Limited by size and quantity of the machinery*
Equipment needed	*Excavator, hauling trucks or conveyor belts, primary and secondary crusher, extractive waste and tailings deposits, equipment for lowering the water table, accommodation for workers; equipment cost is relatively easy to determine*	*Production support vessel with control room, ore pumping and dewatering unit, accommodation units, power generating units and risers for different subsea cutters, transport vessels, generators; cost of equipment could be high*	*Modular submerged cutter(s), riser and positioning barge with pumps, dewatering station, control room, accommodation for workers, generators (in case of remote location), cost of equipment not yet defined*
Energy requirements	*Liquid fuels for trucks and excavators, electricity provided by grid or diesel generators, explosives for blasting*	*Electricity provided by diesel generators*	*Electricity from grid or provided by diesel generators*
Sidewall stability	*Defined by the geotechnical properties of host rock and geological conditions; often a limiting factor for further mine development*	*Since ores are mined on the sea floor there is no problems with sidewall stability*	*Better stability can probably be expected compared to conventional open-pit mining: no erosion, no freezing, balanced hydrostatic pressure, no adverse phreatic surfaces, no weakening due to blast vibrations;*
Hauling	*Trucks or conveyor belts; significant amount of energy and equipment is required*	*Ore is transported in suspension, lower energy requirements due to hydrostatic effects*	*Ore is transported in suspension, lower energy requirements due to hydrostatic effects*
Workforce and safety	*A larger number of workers with different skills are needed, but this depends on the level of automation in the mine; many requirements to assure worker health & safety*	*Moderate to low numbers of workers (special training required for some positions), no need to work in dangerous places due to remote control of the machinery, lower requirements to assure worker health & safety*	*Moderate to low numbers of workers, (special training required for some positions), no need to work in dangerous places due to remote control of the machinery, lower requirements to assure worker health & safety*
Environmental impacts	*Emissions of dust and gases, noise, visual impact on landscape, changes in water table, release of sediments, risks of acid mine drainage, tailing, oil, chemical and lubricant spills, erosion of sidewalls, discharge of mine water, vibrations because of blasting, impacts on biota*	*Impacts on marine biota, dispersion of sediments, risk of fuel, chemical and lubricant spills*	*Smaller risk of fuel, chemical and lubricant spills than in conventional mining, possible impacts on groundwater chemistry, only sidewalls above water table are subject to erosion, lower visual impact on landscape than conventional mining; low water pH can limit use of ¡VAMOS! machinery*
Suitability for different deposit types	*All types of in-land ore deposits, provided there is a sufficient amount of ore close enough to the surface*	*Sedimentary deposits on continental shelves, SEDEX & polymetallic ore deposits on ocean floor*	*Vertical/semi-vertical orebodies, deformed sedimentary deposits, possibly also hydrothermal deposits in veins near surface and other deposits in areas of high groundwater levels; ore hardness could be a limiting factor due to the reduced weight and size of excavators and related hydrostatic effects*
Social acceptance	*Depends on the operation and locality; could be a limiting factor for mine development.*	*Not known*	*High social opposition is not likely, since the main purpose of ¡VAMOS! technology is the exploitation of resources in abandoned flooded open-pit mines, where land is already degraded*

vibrations will be reduced, no toe seepage or erosion of softer rocks due to equalised water pressure, no oxidation of materials in side walls, no differential water pressures in the pit and no frost damage underwater, and since people will not work at the site of extraction there will be no need for very high safety measures. However, the sidewall stability of submerged sediments, tilted layered rocks or tectonically fractured rocks might be reduced in underwater environments compared to above water conditions. However, these are hypothetical assumptions that still need to be confirmed in real-environment tests. If ¡VAMOS! proves that it will lower the stripping-ratio of a mining operation, then less waste rock will need to be removed, further reducing the environmental impact and increasing the cost and energy efficiency of the mining operation.

Table 1 provides a preliminary analysis that has been carried out to provide a comparison between the ¡VAMOS! concept, conventional in-land open-pit mining, and off-shore mining with regards to economic exploitability.

Figure 3: Site preparation for the first field trials in Lee Moor, Devon, UK (September 2017, photo by James Kinsman).

Field trials

Two field trials are planned within the iVAMOS! project, taking place in October 2017 and in spring 2018. The first trial is scheduled for Lee Moor, Devon, UK, at a disused flooded kaolin open-pit extraction site that ceased operation in 2008 (***Figure 3***). The host rocks of the kaolin deposit are Variscan granite intruded into surrounding Carboniferous slates and gritstones. The kaolinite is derived from the alteration of the host rock's feldspar component by multi-stage alteration processes by superheated and meteoric fluids and gasses (Dominy, 1993). The depth of the lake in the open pit does not exceed 25 m. Besides extraction of very soft kaolinite, the ¡VAMOS! machines will also be tested on extracting harder adjacent side walls composed of granitic host rocks.

Figure 4: Smreka open pit iron mine in Vareš, Bosnia and Herzegovina, the second ¡VAMOS! test site (photo by Gorazd Žibret).

The second test site is the abandoned open-pit iron mine Smreka in Vareš, Bosnia and Herzegovina (***Figure 4***). The ore minerals are massive and layered siderite and hematite which are locally silicified (Operta and Hyseni, 2016). The iron-rich layers dip steeply towards the north. This deposit formed as a hydrothermal replacement of the host rocks – limestone and dolomite. The hydrothermal fluids entered the area through a strike-slip fault of regional importance. The southern footwall of the ore body is breccia limestones of Jurassic age, while the north wall is composed of siliceous slates, shales, and slates ("Werfen formation"). The uniaxial compressive strength of rocks found in Smreka pit varies between 44 and 80 MPa.

Besides testing the equipment in real environments, the purpose of the site trials is also to measure different operating parameters. They will be needed to evaluate this newly developed equipment for its potential usefulness for economical exploitation of mineral resources and to compare it with conventional mining techniques. Since one of the most important factors affecting the production rates in mining or civil engineering projects is the performance of the mechanical excavators (Tumac et al., 2007), special focus will be put on determining the excavator productivity (m^3/h) for different types of rocks. In addition to productivity, several other key parameters will be measured, including the determination of typical:

- working hours needed to assemble, operate, maintain and disassemble the ¡VAMOS! equipment;
- power, fuel and lubricant usage;
- machine productivity and net cutting rate for different ores and rock types;
- equipment wear and overhaul costs;
- ore suspension dewatering costs;

- environmental impacts: impacts on water chemistry, suspended particulate matter levels, sediment dispersion, vibrations and noise emissions, etc.;
- social perception of mining when using ¡VAMOS! equipment;
- other relevant parameters.

From the results of the field trials, it will be possible to estimate the industrial viability of the ¡VAMOS! equipment and market up-take possibilities, with special focus on where exactly (what type of deposits and geo-environments) the ¡VAMOS! technology performs better than conventional mining technologies.

Conclusions

¡VAMOS! provides a new mining technique that is expected to be used for reopening of abandoned and flooded open-pit mines because it will allow ore extraction underwater. The reduced stripping ratio due to expected increased wall stability will decrease the surface footprint of a mining operation and require lower energy use, as less unwanted material needs to be removed. The highly automated system functionality significantly reduces safety risks. As there is no need for haul trucks and blasting and because the machinery largely works underwater, there will be less noise and and almost no dust emissions. Less oil and fuel is needed for the operation, reducing the risk of spillages. Energy consumption is reduced as there is no need for constant dewatering and the local water table around an operation will not be affected. All these factors combined make rehabilitation easier at the end of mining operation. Field trials, expected to take place in October 2017 and spring 2018, will provide information on the exact conditions and type of environments where ¡VAMOS! would be preferred option for mineral extraction and will demonstrate the environmental integrity and economic viability of the system.

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