Positioning, Navigation and Awareness of the ¡VAMOS! Underwater Robotic Mining System

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***Abstract*— This paper presents the positioning, navigation and awareness (PNA) system developed for the Underwater Robotic Mining System of the ¡VAMOS! project [1]. It describes the main components of the ¡VAMOS! system, the PNA sensors in each of those components, the global architecture of the PNA system, and its main subsystems: Position and Navigation, Real-time Mine Modeling, 3D Virtual reality HMI and Real-time grade system. General results and lessons learn during the first mining field trial in Lee Moor, Devon, UK during the months of September and October 2017 are presented.**

I. Introduction

Europe estimates that the value of unexploited European mineral resources at depth of 500 - 1000 meters is approximately € 100 billion, and the European Union consumes 25-30% of the world's metal production [2]. Despite the efforts to develop recycling technologies and material science, the EU's industry dependency on metal imports is growing every year (200 million tons of minerals), in which 14 mineral raw materials were explicitly named as highly critical for the industry [3]. In answer to this European concern a research and innovation action program was created regarding the development of new technology for automated mining, mining of small deposits and also alternative mining methods [4]. One of these projects is ¡VAMOS! , that stands for Viable Alternative Mine Operating System, funded by the European Unions Horizon 2020 research and innovation programme, addresses the development of a prototype underwater mining system to extract raw materials from flooded open-pit mines. These inland mines have been considered depleted in the past because with previous mining techniques it was not economically viable anymore to continue operations. Today, with rising prices of certain rare ores it becomes interesting again to re-open abandoned mines in order to access deeper seated minerals. However, conventional mining techniques require high treatment and dewatering costs. Moreover, from an environmental perspective, it is desirable that the water table of these flooded inland mines is not changed. Therefore, the ¡VAMOS! project aims to develop a new remotely controlled underwater mining machine (MV), associated launch and recovery vessel (LARV) and support and survey autonomous/remote operated underwater vehicle (AUV/HROV), which provides a mining technique that is environmentally and economically more viable than the state-of-the-art [5], [6].

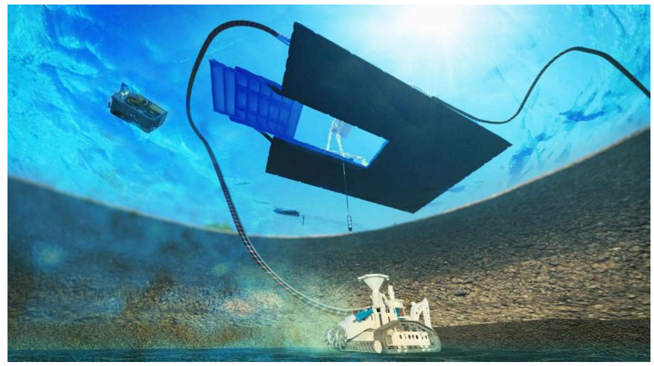

Fig. 1. H2020 ¡VAMOS! project concept.

The challenge in tele-operating a large underwater mining vehicle is that there is no direct inter-visibility, which makes precise control difficult. For the proper and efficient operation of the ¡VAMOS! Underwater mining system, the operators in a remote control cabin (CC) at the surface, cannot rely only on raw data streams from the sensors on the MV, LARV and the EVA AUV/HROV, and must have all the perception and localization sensors data fused, integrated, and presented in a user friendly and intuitive virtual reality environment.

For that, all navigation sensors are combined and fused to provide real-time, accurate and precise information about the localization and orientation/attitude of all ¡VAMOS! systems (MV, LARV and EVA AUV/HROV). This real-time navigation information and the mine perception data from multibeam, 3D sonar and structured light systems, feed the 3D mine modeling system [7] [8] [9] that updates the 3D model both with real-time data and with off-line survey data from the EVA AUV. The 3D mine model, navigation data and sensor data, feed the Virtual Reality interface providing operators friendly 3D visualization of mine and all the ¡VAMOS! vehicles, as well as, the overlay of sensor data and mining operation information.

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In addition to the mine pre-surveys and periodic mine surveys, the EVA AUV can support the MV operation. It can improve the perception of the mining process by allowing a controllable field of view of on board multibeam sonar and SLS sensors. Can allow visual inspection of the MV underwater, assist some tool change operations underwater and even support the MV recovering with the alignment of the bullet catch.

A new approach to Laser-Induced Breakdown Spectroscopy (LIBS) system was developed for ¡VAMOS! , capable of analyzing complex mineral samples, enabling the real-time grade control of the slurry.

This paper is outlined as follows: in section II the PNA system architecture and sensors are presented. The multi-sensor navigation system is detail in section III,

Results from PNA system, obtained in the field trials done in a flooded open pit mine in Lee More, Devon, UK during the months of September and October 2017 are presented and analyzed.

II. Architecture and Sensors

The PNA system is divided by all the vehicles: MV, LARV, the EVA AUV/HROV and also the CC, see Fig. 14 for an overall of all systems and Fig. 2 for a detailed view of the MV sensors. The sensors and computational systems installed in each Vehicles are listed in Table I.

TABLE I
SENSORS TABLE

MV	Kongsberg M3 Multibeam/Imaging Sonar; Coda Echoscope; Impact subsea Altimeter; KVH1750 IMU; Evologics uSBL; Pressure sensor; Cameras/SLS; Sidus P&T.
LARV	3x RTK dual frequency dual constellation GNSS; 3x Evologic SBL transponders; 5 Cameras and winch sensors; GNSS acquisition and processing computer.
EVA	Kongsberg M3 Multibeam/imaging Sonar or Coda Echoscope; KVH GEO FOG 3D INS; Evologics S2C R 42/65 USBL OEM uSBL; Nortek DVL 1MHz; Pressure sensor; 3x Custom Cameras/SLS systems with onboard processing; Main computer; Sonar processing Computer.
CC	RTK GNSS base station; Perception, Position and Navigation Computer; VR computer; RT Mine Modelling computer; Sonar processing Computer; Cameras streaming Computer.

The flow of information between the sensors systems on the vehicles (MV, LARV and EVA AUV) and the processing modules running on the PNA computers on the CC is depicted in Fig. 3. Additionally, to systems presented in Fig. 3, there is the an additional subsystem, the Grade Control System that works stand alone.

Fig. 2. PNA sensors assembled in ¡VAMOS! LARV.

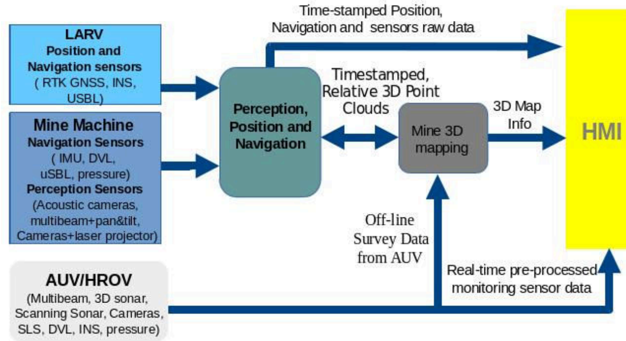

Fig. 3. PNA Proposed Architecture

The following sections details the main PNA subsystems.

III. Navigation and Positioning

The multi-sensor position and navigation system is composed of an acoustic positioning network common to all vehicles, plus several sensors in each vehicle that are fused to compute an accurate estimate of the global pose (position and attitude) of each vehicle - MV, LARV and AUV/HROV.

Both the AUV/HROV and the LARV are equipped with GNSS receivers, which allow the determination of global position directly (for the AUV/HROV only when at surface). For the LARV case, a multi-antenna, multi-frequency, RTK-GNSS system also allows the computation of the vehicles complete pose, including position and attitude. This information is used to geo-reference the acoustic positioning measurements obtained from the SBL system attached to the LARV and the iUSBL systems in the vehicles. The SBL system, composed of 3 transponders near to the LARVs corners, tracks the AUV/HROV and MV. Both vehicles are equipped with acoustic iUSBL transponders. Through the iUSBL transponders, the underwater vehicles can determine their relative position and orientation in relation to the SBL network frame (Fig.4). Transforming these relative measurements into global position observations is straightforward, by considering the LARVs pose, communicated through the umbilical or by acoustic modem functionality of the acoustic positioning system in the case of the AUV/HROV.

Despite the ability to compute the global position of

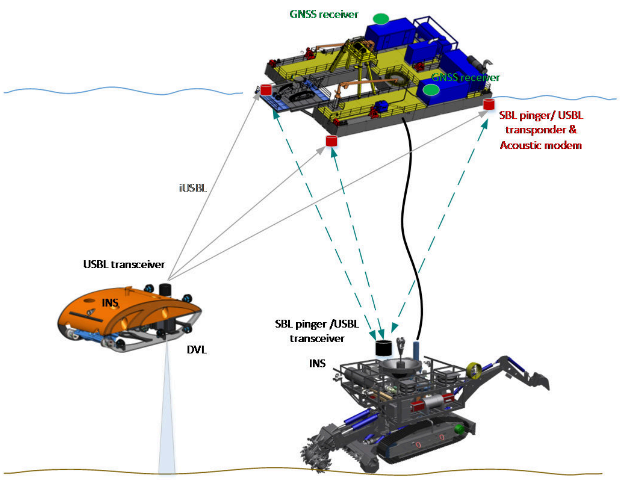

Fig. 4. ¡VAMOS! Underwater Position System.

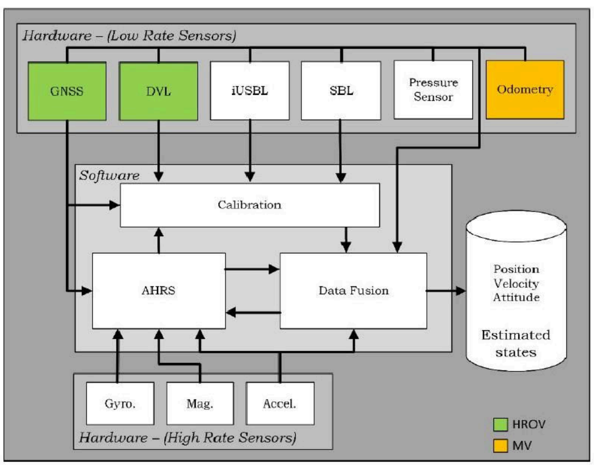

Fig. 5. Functional architecture of localization system

all vehicles with only the SBL/iUSBL and LARV GNSSs, the integration/fusion of all other sources of information is mandatory to increase the robustness of the solution. Robustness is improved by catering for multi-paths acoustics (due to the enclosed environment). The fusion with the other information sources also allows an increase in the estimation rate, reduction of the estimate uncertainty and estimation of additional pose states such as attitude and velocity. Therefore, the underwater vehicles carry extra sensors, whose measurements are fused with the information from the acoustic positioning system. The AUV/HROV carries an INS unit, integrating a triaxial accelerometers, FOG gyroscopes and magnetometers as well as a dual frequency triple constellation GNSS receiver. There is also a DVL system for measuring the linear velocities relative to the mine bottom, when close to it, or to the water column. DVL sensors produce direct observation of linear velocity, as opposed to the INS system that determines linear velocity by integration of measured accelerations. This causes the INS velocities to drift with time, unlike the DVL case, for which a bounded error is expected. Nevertheless, DVL alone does not fully replace an INS, as it does not provide information about the vehicle attitude. Moreover, the INS provides measurements at a fix rate, while the DVL is subjected to dropouts resulting from noise, multi-path or loss of range. For that reason, the integration of INS and DVL is advantageous, as they complement each other. A pressure sensor gives an indication of the vehicles depth underwater. The MV carries a fibre optic gyros (FOG) based IMU (KVH 1750 mounted in a turn table mechanism for initial bias estimation and north seeking [10]), from which the vehicles attitude is determined. A pressure sensor allows the direct determination of the vertical position with respect to the surface. Global positioning is obtained from the acoustic positioning system. An Extended Kalman Filter, independent for each vehicle, is responsible for fusing all sensor information to compute their full pose in real time (Fig.5).

This real time navigation solution and all of the point cloud data streams from the Multi-beam profilers, 3D Sonars, and SLS systems feed the continuous-time SLAM and mine modeling software.

IV. Real time mining model

In the ¡VAMOS! project one important component to enhance situational awareness of the operator is the real time mining modeling system since it is well known that a map of the environment in addition to the raw sensor data is extremely helpful in supporting remote control and enhancing spatial awareness. In order to achieve this, the real time mining modeling system fuses measurements from the perception sensor systems, such as multi-beam sonar, 3D imaging sonar, and structured light scanners, into a consistent 3D representation. Mapping algorithms based on a signed distance function (SDF) voxel map and sensor models were developed to integrate measurements taken with varying accuracy and noise properties. In order to store large maps with low memory consumption we need to encode free space efficiently. To do this we store the SDF voxel map in an tree structure. We integrate the different sensor modalities by following the generalized sensor fusion approach proposed by [11]. A SDF map is a beneficial surface representation because noisy measurements are smoothed over multiple observations. Starting with a pre-mining site survey the 3D environment model is updated online during operations. As the mine changes over time, due to the mining operations themselves the internal representation of the mining environment needs to be constantly updated based on new sensor observations. Since most of the model representing the mine does not change, only small volumes need to be updated frequently.

The resulting 3D terrain map is presented in a virtual reality to the operator via the ¡VAMOS! Human Machine Interface described in the following section. In Fig. 6, in the virtual reality system. The mapped volume has a size of roughly 1000m x 1000m x 150m. For visualization purposes the map was reduced to 10cm resolution for the above-the-water terrain mesh. Below the water surface the data was

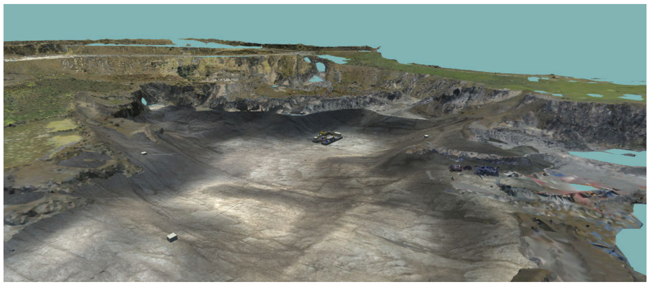

Fig. 6. Above-the-water and underwater model of the Lee Moor mine site created from LiDAR and sonar scans.

Fig. 7. 3D Virtual Reality (VR)

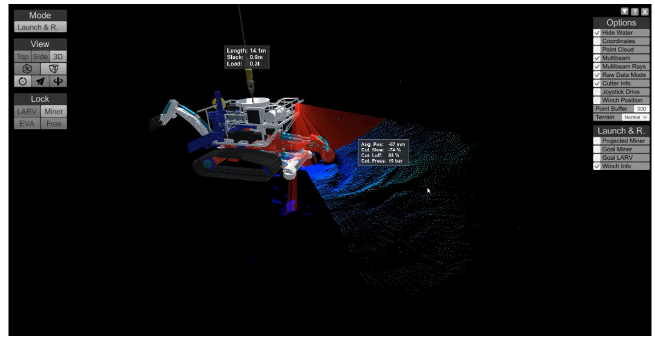

Fig. 9. Overlay of information possibilities.

Fig. 10. Control cabin HMI with virtual reality interface.

processed in a 25cm grid.

V. 3D Virtual Reality based Human-machine interface

The 3D Virtual Reality based Human Machine Interface (HMI) has two main componentes. The first for assisting the operator with remote awareness and control of the mining vehicle, and the second, the equivalent system for the Launch and Recovery Vehicle (LARV).

For both components, the novel central element of the approach is the creation of a 3D Virtual Reality (VR) model of the entire mining operation. This model includes the mine terrain, the mining machine, the Hybrid Remotely Operated Vehicle (HROV), the support barge, the riser system, and any other relevant static structures. This model is dynamically adjusted so that it faithfully replicates the real operation at all times. This model is used to visualize all aspects of the operation and to deliver a range of functionalities. This approach has several advantages over traditional visualization systems. These include: the ability of the operator to move their viewpoint to any desired position, the ability to overlay pertinent information on the view, the fact the system provides a clear view independently of turbidity, and that it is an enabling technology for driverless operation.

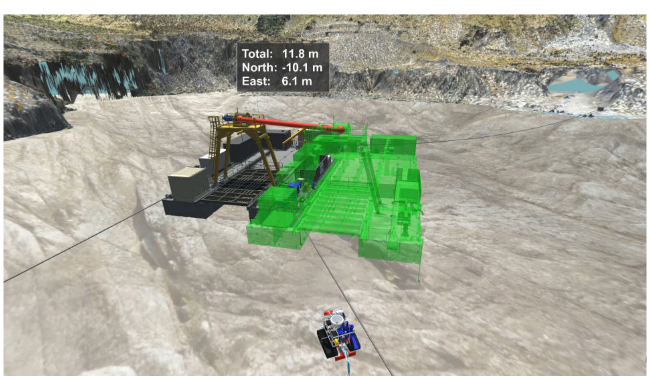

Fig. 8. LARV position and target position over the MV.

VI. Grade Control System

A prototype system for ore grade analysis was developed, based on Laser Induced Break Down Spectroscopy (LIBS), which allows the evaluation of the slurry composition by high-resolution spectroscopic analysis of a plasma generated by a pulsed laser in the target sample. While the technique enables straightforward identification of pure elements, including light elements such as Li and B, identification and quantification in the context of complex mineral samples is quite challenging due to matrix effects and sample variability [12]. To tackle this challenge the prototype is being used to build a multi-dimensional LIBs spectral database that will feed a dedicated Self-learning Artificial Intelligence (AI) software system, introducing more efficient and robust identification and quantification methods [13].

In this context, the system comprises two key components, a hardware component and a software component. The hardware component is a laser based system, suitable

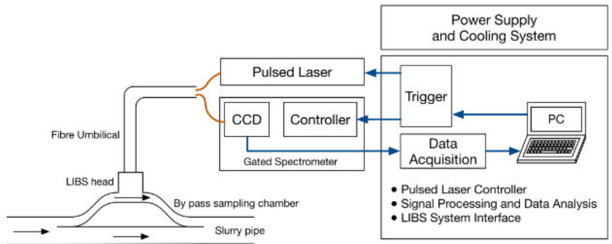

Fig. 11. Architecture of the LIBS system.

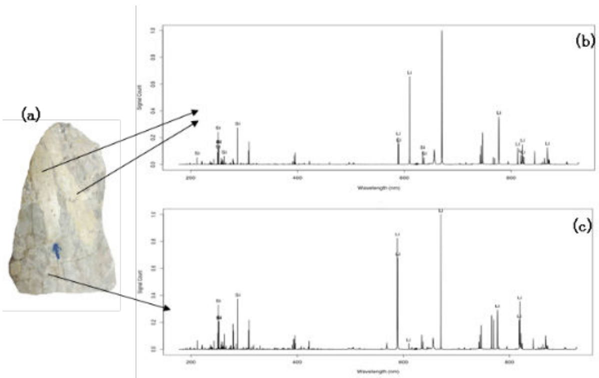

Fig. 12. Example of mineral sample from the Database (Lithium ore), with composition mapping from the LIBS spectra, and reference analysis systems

for plasma spectroscopy analysis of the slurry composition, assisted by high resolution fibre optic spectrometer, including a low cost UV-Vis analysis system. The software component is a dedicated Firmware for implementation of a LIBS AI system, coupled with a big Data Geological database (LIBs, UV-Vis-NIR spectra, and other analytic standards) built with geological reference materials, pure minerals and mining samples. The modular nature of the hardware, combined with the innovative nature of te signal processing approach enabled a Smart Libs technology that can perform in different environments. The system was first set up in the Lab to build a mineral spectra Database, with several samples of pure and complex minerals (Fig 12), of interest to the mining operations.

VII. Field Results

Integrated ¡VAMOS! system field trials were performed at the Lee Moor china clay mine (Fig. 13) in Devon, UK. This was a complex setup involving logistics of 15 container transport trucks and construction works. The PNA test period spanned a period of almost two months and involved both the on-site setup, calibration and evaluation.

A pre-survey of the open pit was performed in 4 missions of the EVA AUV, trajectories are depicted in Fig 15. This information was integrated in the mine model used in the virtual reality human-machine interface (Fig. 7). The position and attitude of the the vehicles calculated by the PNA and integrated in the VR system, allowed for precise sensor information fusion and efficient vehicle control. The VR interface integrated information from the multiple vehicles in the operation in a consistent interface (Fig. 16) and was also seamless integrated with other conventional command and control interfaces in the CC. During the tests one of the major findings was the high level of usability of the system both by MV trained operators and non trained personal. Multibeam sonar data in imaging mode was used not only to provide awareness in very restricted visibility conditions (see Fig. 19 and Fig. 18) but also in profiling mode (Fig. 17) for cutting volume assessment.

The LIBS system prototype (Fig 20) was put into operation at the mine site in Lee Moor. Different types of samples,

Fig. 13. Lee More, Devon, UK Field Tests.

Fig. 14. ¡VAMOS! Developed Systems.

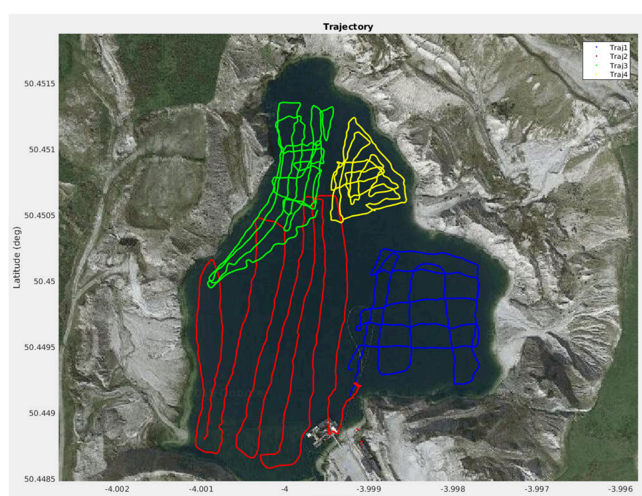

Fig. 15. Pre-Survey bathymetry missions with EVA AUV.

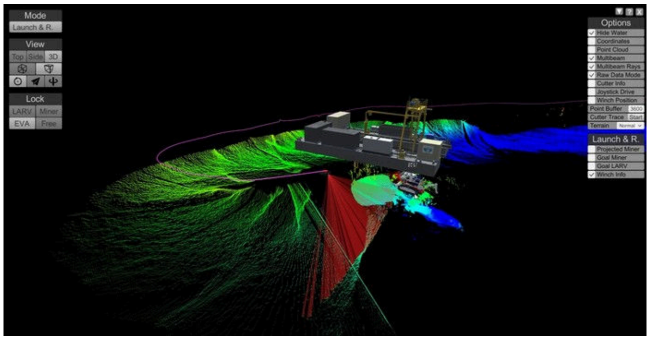

Fig. 16. M3 Scanning of 3 MV Cuts.

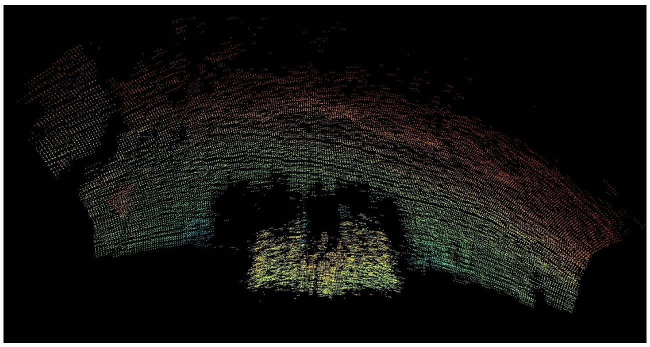

Fig. 17. Boom cutter multibeam sonar modeling.

including Kaolin, granite and other rocks, were collected on site, from the slurry output, from different points of the dewatering station, and from the mouth of the Mining Vehicle. All were analyzed on site and compared against the reference Database.

The system was able to classify very clearly the different types of Kaolin and granites (Fig. 21). An unknown black sample was also standing out in the data classification. By running the collected spectra against the reference database the AI software was able to identify the sample as a Tourmaline mineral containing Lithium. These results were later confirmed by the mine geochemical reports and geologists.

VIII. Conclusions

The ¡VAMOS! system development was the first time that an innovative robotic system comprising underwater

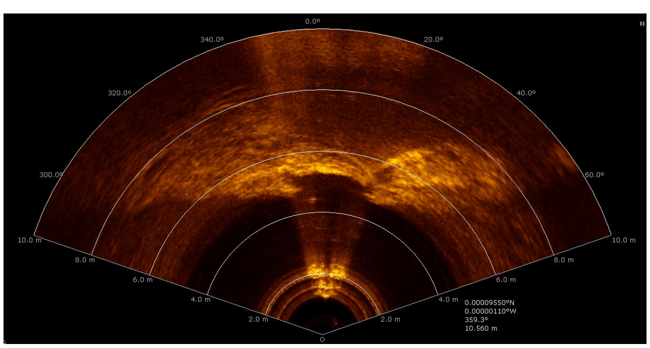

Fig. 18. Boom cutter sonar imaging.

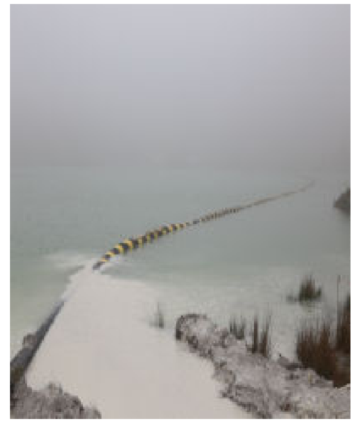

Fig. 19. Lee More Water turbidity.

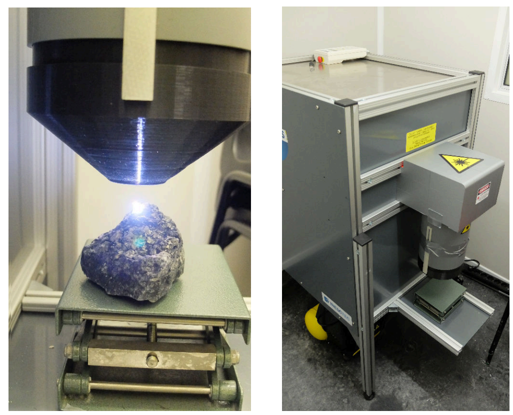

Fig. 20. LIBS system prototype in operation at Lee Moor field trials.

mining vehicle, support AUV, launch and recovery vessel and associated equipment was deployed and integrated in a real flooded pit mine with mining operation.

The Position, Navigation and Awareness system of the ¡VAMOS! robotic system was thus developed, integrated and validated in real operational conditions. The process of integration and setup of all the PNA equipment in the multiple ¡VAMOS! vehicles and CC was a complex engineering process, involving various engineering teams and addressing mechanical; hardware; software and communications aspects. This process of configuration, parametrization and calibration of a vast number of subsystems in multiple assets toke around 2 to 3 weeks.

From the trials it was evident that the PNA is critical for the operation of the mining system. It was possible to have the position of the vehicles, map and perceive the environment and how it changed with the mining process. The EVA AUV/HROV was easy to deploy, capable to do both the pre-surveys of the mine pit and also in assisting the mine process operation, providing external viewpoints of the MV environment.

The 3D mine modeling process was able to fuse the multibeam sonars (from multiple vehicles) information with the associated position and navigation data into models used to feed the VR framework.

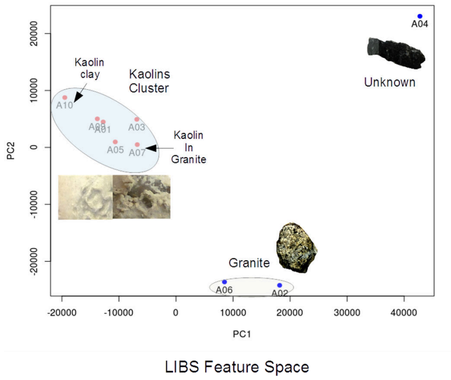

Fig. 21. Classification of the different samples collected and characterized at Lee Moor according to the features of their LIBS spectra.

During field trials the VR HMI shown to be a very powerful tool, providing the operator with an enhancement awareness of all the ¡VAMOS! elements (MV, LARV, AUV/HROV) and of the environment allowing a better control of the mining process. It was able to handle articulable models of the mobile machines, the mine environment, update all models with the real-time data from position and all articulations, add overlays of useful information for the operator, and the real-time terrain modeling.

The LIBS System usefulness was demonstrated in the field trials although not deployed underwater in the MV. LIBS was able to identify targets in a complex scenario, as long as proper training with reference materials from the target mine is performed. The results show the viability of using LIBS as an ore grading tool. Next steps of development include hardware improvements to enable operation underwater or directly in the slurry pipe. Such solutions are at reach using for instance sampling probes with compressed air and using double pulse lasers techniques [14] [15].

The testing, validation and benchmarking of the structured light systems and their impact on the perception and awareness process was not possible to be done at Lee Moor due to the site specific conditions, namely the high level of fine silt (from china clay) causing extreme water turbidity. Despite the high number of suspended particles in the water there was very limited impact on the sonar data, only with a small decrease on the DVL effective range due to soft ground and reduced reflections.

In the next field trials to occur in the Vares mine in Bosnia the SLS system is to be validated. This is a mine with a much hard rock producing very different water turbidity conditions.

Ongoing work is been pursued in the automation of the PNA initial setup and calibration procedures in order improve the global process efficiency.

The planned field trials in the new site will allow for the test of the system in different operational conditions, namely with higher depths, different pit conditions and different set of minerals on the walls and bottom of the pit. The gathered added information will also allow for a more complete characterization of the performance of the developed system and to evaluate the impact of the PNA in mining production process.

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