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<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
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<tr>
<td>CC</td>
<td>Control Cabin</td>
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<td>DVL</td>
<td>Doppler Velocity Log</td>
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<tr>
<td>HROV</td>
<td>Hybrid Remotely Operated Vehicle</td>
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<td>ICD</td>
<td>Interface Control Document</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<td>IMU</td>
<td>Inertial Measurement Unit</td>
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<td>INS</td>
<td>Inertial Navigation System</td>
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<tr>
<td>iUSBL</td>
<td>inverted Ultra Short Baseline</td>
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<td>LARV</td>
<td>Launch &amp; Recovery Vessel</td>
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<td>MV</td>
<td>Mining Vehicle</td>
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<td>NMEA</td>
<td>National Marine Electronics Association</td>
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<td>NTP</td>
<td>Network Time Protocol</td>
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<td>PC</td>
<td>Personal Computer</td>
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<td>PNA</td>
<td>Positioning, Navigation and Awareness</td>
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<tr>
<td>PPS</td>
<td>Pulse Per second</td>
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<td>RTK</td>
<td>Real Time Kinematic</td>
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<td>SBL</td>
<td>Short Baseline</td>
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<td>SLAM</td>
<td>Simultaneous Localization and Mapping</td>
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<td>SLS</td>
<td>Structure Light System</td>
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<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
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<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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1 Executive Summary

This document reports the work developed under the scope of deliverable D4.4 - Multi-sensor navigation system, as specified in Grant Agreement, 642477, ANNEX 1 (part A), Work Package 4; consisting of a prototype demonstrator for the navigation system of ¡VAMOS!. Deliverable D4.4 results from the activities of subtask 4.2.1 “Multi-sensor Navigation System”.

The Multi sensor Navigation System prototype demonstrator will provide the MV Position and attitude that allow the representation of the vehicle in the VR environment, the perception data to feed the Mine Modelling system to update the VR environment map in real-time, both from sonars and visual based range sensors (SLS), and as well imaging for the operator.

The multi-sensor navigation system incorporates all necessary hardware and software components that establish 4 subsystems: an acoustic positioning system for enclosed mines, a vision perception system, a structured light system (SLS) and an acoustic underwater imaging system.

The activities contributing to deliverable 4.4 started in September 2015 and ended in July 2017. Currently, all components are fully developed and integrated into the prototype demonstrator.

The subsystems were tested in the Lab and in relevant environments where possible. Integration in the CC, MV and LARV has also been completed.

Full system validation of the multi-sensor navigation system in a real environment will only be possible in the first field trial at Lee Moor Mine.
2 Introduction

2.1 The VAMOS Project

Estimates indicate that the value of unexploited European mineral resources at a depth of 500-1,000 meters is ca €100 billion, however, a number of physical, economic, social, environmental and human constraints have as yet limited their exploitation. ¡VAMOS! will provide a new Safe, Clean and Low Visibility Mining Technique and will prove its Economic Viability for extracting currently unreachable mineral deposits, thus encouraging investment and helping to put the EU back on a level playing field in terms of access to strategically important minerals. Deriving from successful deep-sea mining techniques, the ¡VAMOS! mining solution aspires to lead to: Re-opening abandoned mines; Extensions of opencut mines which are limited by stripping ratio, hydrological or geotechnical problems; and opening of new mines in the EU. ¡VAMOS! will design and manufacture innovative automated excavation equipment and environmental impact monitoring tools that will be used to perform field tests in four mine sites across Europe with a range of rock hardness and pit morphology. ¡VAMOS! will:

- Develop a prototype underwater, remotely controlled, mining machine with associated launch and recovery equipment
- Enhance currently available underwater sensing, spatial awareness, navigational and positioning technology
- Provide an integrated solution for efficient Real-time Monitoring of Environmental Impact
- Conduct field trials with the prototype equipment in abandoned and inactive mine sites with a range of rock types and at a range of submerged depths
- Evaluate the productivity and cost of operation to enable mine-ability and economic reassessment of the EU's mineral resources.
- Maximize impact and enable the Market Up-Take of the proposed solutions by defining and overcoming the practicalities of the concept, proving the operational feasibility and the economic viability.
- Contribute to the social acceptance of the new extraction technique via public demonstrations in EU regions.

2.2 Deliverable D4.4

2.2.1 Objectives

The final outcome of the deliverable is a demonstrator prototype for the navigation system, with integration of multiple sensors installed on board the MV, LARV, CC and HROV. The demonstrator prototype is composed of the following subsystems:

- Acoustic positioning for enclosed mines, including iUSBL and SBL methodologies
- Vision perception system to be installed on the MV and the HROV
- Structured light system with laser sights for close range 3D perception
- Acoustic imaging system for underwater environment modeling

2.2.2 Approach

All four subsystems involve the integration of several sensors, which includes the development of hardware, as well as all necessary software interfaces. The development process followed a system engineering approach, taking as input the requirements stated in deliverable D2.5 and the interface control document (ICD) of sensors selected in WP3. The development of all components was followed by extensive laboratory and field operation
tests. To ensure a smooth integration of all subsystems in the MV, CC and LARV at mine site in WP5, the systems were taken to SMD and Damen for a preliminary integration and validation.

### 2.2.3 Timetable

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3 Multi-sensor navigation system

This section starts by giving an overview of the subsystems and their interactions, and later in the following subsections, provides a more detailed description of the main subsystems that encompass the Multi Sensor Navigation system and their interaction with other subsystems.

The multi-sensor navigation system is composed of an acoustic positioning network common to all vehicles, plus several sensors in each vehicle that provide measurements about each vehicle’s individual pose. The multi-sensor navigation system encloses all hardware and software blocks necessary 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 vehicle’s 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 LARV’s 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. Transforming these relative measurements into global position observations is straightforward, by considering the LARV’s 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 all vehicles with reliance only on the SBL/iUSBL and GNSS networks, 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). Use of 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, composed of 3 accelerometers, 3 gyroscopes, 3 magnetometers and a GNSS receiver. The INS provides measurements of all pose states of the AUV/HROV. There is also a DVL system for measuring the linear velocities relative to the mine bottom. 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 vehicle’s depth underwater.

The Mining Vehicle carries a fibre optic gyro (FOG) IMU, from which the vehicle’s 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. The Extended Kalman Filter implementation is detailed in Deliverable D4.6. 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 modelling software.
3.1 Acoustic positioning system for enclosed mines

The ¡VAMOS! environment scenario, the open pit mines, can present some challenging problems in terms of multipath acoustics, noise and the logistics for the setup of the positioning network. The concept for the ¡VAMOS! acoustic positioning system involves combining a Short Baseline (SBL) network installed on the LARV plus iUSBL devices onboard the AUV/HROV and the MV. In order to geo-reference measurements from the acoustic system, the position and attitude of the LARV must be determined. This is accomplished through a triple antenna GNSS baseline assembled on the LARV.

In the particular operation on open pit mines, with the LARV typically positioned above the mining machine in a central position, it allows good line of sight and reduced obstruction, between the SBL and iUSBL transponders, and has the advantage of not requiring any additional setup to install the acoustic positioning system. The acoustic paths and configuration are thus favourable, and compared to LBL solutions provides the advantages of no additional setup requirement and no additional restrictions to the mining operation (such as mooring lines or bad relative localization). It is also of note that depending on the mine morphology placement of multiple beacons could possibly be needed in an LBL solution. In addition, the LBL beacons in principle would need to be placed either in buoys or moorings. Placement at the bottom can pose problems due to the mining procedure and environment morphology changes. LBL setups would be affected by errors in the positioning of the beacons that could vary during the operation.

The SBL/iUSBL setup can also take advantage of the high quality of positioning of the LARV and precise knowledge of the baseline. The iUSBL operation can be used to provide localization information in real-time for the AUV/HROV navigation/control system, which does not have synchronization via cable (unlike the MV), thus providing additional flexibility in the global PNA system. The developed solution therefore provides not only operational advantages but also accurate posing taking note of the ranges of operation and typical mine morphologies.

3.1.1 Acoustic system

The SBL network consists of three transponders, Evologics Mini Modems 42/65 (Figure 1), mounted on fixed locations onboard the LARV, defining relative baselines of approximately 15 to 20 meters. The iUSBL devices, Evologics USBL 42/65, assembled on the MV and the AUV/HROV, interact cyclically with the SBL baseline, allowing the SBL system to track each iUSBL target and inversely enabling each iUSBL transponder to self-localize in relation to the SBL network. So when the SBL network pings the vehicles, both vehicles can have an iUSBL measurement at the same time, and when one of the vehicles replies the SBL network gets an SBL position update for that vehicle.

Figure 1: SBL transponder being tested on the pool
Each SBL transponder communicates with external systems through Ethernet. To ensure a common time between all SBL elements, each transponder receives PPS synchronization signals through a dedicated line and NMEA information flows through the Ethernet connection. A junction box, placed in between the transponders and the processing unit (Figure 2), forks the PPS signal and provides a unique IP address to each transducer. On the iUSBL side, the communication is established by Ethernet, with synchronization references also sent by Ethernet using the NTP protocol and PPS in the case of the MV or the AUV/HROV when at the surface.

![Connection diagram of the SBL system](image)

Figure 2: Connection diagram of the SBL system

Additionally to the positioning function, the SBL and iUSBL devices operate as acoustic modems, allowing messages to be exchanged between vehicles. That functionality is managed by the device drivers developed for the SBL and iUSBL systems.

### 3.1.2 Multi-antenna GNSS

The LARV’s positioning system is designed to provide global positioning and attitude with high accuracy. The system is composed of three multi-frequency, multi-constellation GNSS receivers and an IMU on-board the vehicle, plus an additional GNSS base station, to be installed on land. As illustrated in Figure 3, corrections broadcast by the terrestrial base station reach the GNSS1 receiver on board the LARV, allowing global position determination using the Real Time Kinematic (RTK) method. This procedure allows the global positioning of the LARV with centimetre level accuracy. Corrections from the base station to the LARV are sent through a radio link.

Besides computing the LARV’s global position, GNSS1 provides corrections to the other receivers on board, establishing two baselines for relative positioning. The baseline processing is accomplished through the RTK method in mobile base mode, allowing the relative positioning of receivers GNSS2 and GNSS3 with respect to GNSS1. A data fusion algorithm, based on the Extended Kalman Filter, was developed to combine all GNSS measurements in order to compute the LARV’s global position, attitude and velocity.
3.1.3 System testing and installation

A test platform was developed for holding the equipment related to the LARV’s acoustic positioning system. The platform depicted in Figure 4 allowed the SBL transponders to be lowered up to 3 meters underwater to maximize the system’s performance. Besides SBL, the testing platform also carried the multi-antenna GNSS system, allowing full testing of the LARV’s acoustic positioning system. In the preliminary field tests, the iUSBL device was carried by the AUV/HROV. A fixed GNSS base station (Figure 5) was used on site to provide correction to the LARV’s system, following the architecture specified in Figure 3.
During the preliminary field tests all system components achieved the specified requirements. All system components have been installed on board the corresponding vehicles. The SBL system was fixed to the LARV using a mechanical holder (Figure 6), which allows each transponder to be lowered up to 3 meters underwater, and to be retracted when maneuvering in shallow waters. The three transponders establish acoustic baselines of approximately 15 and 20 meters. The multi-antenna GNSS system was also installed on top of the LARV’s winch tower, ensuring permanent clear sky view. The sensitive electronic equipment was installed inside the E-Container. The iUSBL transponders and all necessary equipment were assembled on board the mining machine (Figure 7) and the AUV/HROV (Figure 8).
3.2 Vision perception system covering the MV and HROV operations

The vision perception system consists of a set of stand-alone underwater colour cameras with dedicated illumination that provide real time video stream for monitoring the operation of the HROV and the MV. This system is composed of cameras with different characteristics, including two Kongsberg OE14-110 analog cameras and several high sensitivity digital cameras. The digital cameras support high frame rates, allowing a multiplexed operation to serve two purposes – provision of the real time video stream and support of the SLS system. The two Kongsberg cameras are mounted on the tool arms of the Mining Vehicle to give close feedback about the operation of each tool. Each camera is paired with a 4200 lumen spotlight, Teledyne LED-R-4200.

Three SLS systems are installed on top of the three corners of the MV, plus an additional camera, mounted in a Pan & Tilt system dedicated almost exclusively to video streaming. Three SLS systems are available on the AUV/HROV to sense the environment ahead and below. Each camera from the SLS system is coupled with a custom LED illumination system, depicted in Figure 10, composed of 7 LEDs. Both the camera and the LED module can be triggered simultaneously to obtain a properly exposed color image. Tests performed in a dark underwater scenario, illustrated in Figure 11, show that the ideal exposure time varies between 5ms and 15ms.
Figure 9: Vision perception system installed on a pan and tilt unit, assembled on the Mining Vehicle

Figure 10: Initial (right) and final (left) prototypes of the LED illumination for the SLS system enclosed in a watertight housing

Figure 11: Images resulting from different exposures obtained in the dark with illumination provided by the LED set. Exposure times of 5ms (left), 10ms (center) and 15ms (right)
3.3 Structured light system with laser sights
Each structured light device is composed of a high sensitive digital camera complemented by an LED illumination system and a rotating line laser projector, working together to provide optical imaging and/or 3D optical information. The system passed a prototype phase, with all components assembled together inside watertight housings with underwater connectors, as depicted in Figure 12.

![Figure 12: Picture of the initial SLS system prototype, depicting the LED illumination and laser projector inside the left cylinder and the digital camera inside the right cylinder](image)

An embedded system, inside the cylinder holding the LED and laser projectors, is responsible for triggering the projectors (LED and Lasers) and the camera, allowing control of all the timings with an accuracy of microseconds. This embedded triggering system is synchronized with a PPS ensuring that all SLS systems are completely synchronized. To acquire a structured light image (Figure 13), with the laser line visible, both the laser line projector and the camera are triggered simultaneously. Contrarily, to acquire a visible image (Figure 11), the LED lighting system is triggered in conjunction with the camera.

![Figure 13: Structured light image obtained by triggering the laser projector and the camera at the same instant.](image)
The prototype watertight glass housings, equipped with underwater connectors, were tested under pressure, reaching up to 130 bar without collapsing, equivalent to a water depth of 1300 meters, which is far beyond the depth experienced in the context of ¡VAMOS!. Pictures of the pressure tests are depicted in Figure 14.

Figure 14: Pressure tests performed on the underwater housings using a pressure chamber

The final release of the SLS system comprises a calibrated frame holding the two cylinders, one for the laser projector and LED illumination and the other for the camera system (Figure 15). Besides the mechanical enhancements, the final SLS version features improved electronics with smaller size and a more accurate synchronization system.

Figure 15: Project drawings of the final SLS version

All SLS systems have been assembled and mounted on board the Mining Vehicle and the HROV, as illustrated in Figure 16 and Figure 17.
3.4 Acoustic Modeling System

The acoustic modeling system supplies real time visual feedback to the awareness system and simultaneously provides geometric information to aid localization and support navigation. Therefore, it plays an important role all across the PNA system. The acoustic modeling system is based on two devices: the Echoscope Coda Octopus and the M3 Kongsberg multi-beam.

3.4.1 M3 Kongsberg multi-beam sonar

The M3 multi-beam sonar is a versatile device that offers not only the standard multi-beam profiling mode but also sonar imaging functionality. The profiling mode produces an array of 256 narrow beams, with angular resolution of 1.6° across-track by 3° along-track, with a refresh rate up to 40Hz. Due to the reduced footprint of each beam, the profiling mode is the most suitable for geometric modeling. On the other side, the imaging mode is characterized by a wide vertical beam-width up to 30°, allowing the acquisition of an underwater acoustic image,
ideal for situational awareness and obstacle avoidance. The acoustic image is produced by representing the back-scattered energy as a function of range and beam orientation.

The communication between the PNA PC and the M3 sonar is established through an Ethernet connection. It allows configurations to be sent from the PNA PC to the sensor, and raw data to flow in the inverse direction. As illustrated in Figure 18, a proprietary software package is mandatory to perform the direct interface with the sensor and execute beamforming. The data resulting from beamforming becomes accessible to the user through a TCP socket.

![Diagram of the interface with the M3 multi-beam sonar](image)

Figure 18: Diagram of the interface with the M3 multi-beam sonar

Both the HROV and the Mining Vehicle have provision to carry the M3 multi-beam sonar. On the AUV/HROV, the M3 multi-beam sonar is rigidly mounted, as illustrated in Figure 19. On the Mining Vehicle the M3 is mounted on a pan and tilt unit (see Figure 9), allowing its orientation to be changed by the operators.

![M3 multi-beam mounted on the HROV](image)

Figure 19: M3 multi-beam mounted on the HROV

### 3.4.2 Echoscope Coda Octopus

The Echoscope Coda Octopus is a high definition 3D imaging sonar, capturing a full 3D images per ping. The highest frame rate of 12Hz produces a 3D movie of the underwater scene, offering valuable information for positioning, navigation and spatial awareness.
The integration of the Echoscope Coda Octopus in the PNA system follows the diagram from Figure 20. A dedicated Time Sync Board provides electric power and time references to the sensor head. Alongside, an Ethernet connection transports the raw data from the sensor head into an embedded system running the proprietary Data Interface Unit (DIU) software modules, responsible for performing the data acquisition from the sensor head and converting the data into a Cartesian point cloud. At the output, 3D data becomes available to the final user through a UDP socket. In parallel, a Control/Status line, connecting all components, sends control messages from the PNA PC to the sonar head, while feedback about the sonar operation is sent back from the sonar head to the PNA PC. Time references are supplied by the PNA PC, based on its synchronized internal clock, and redirected to the sonar head by the Time Sync Board. The driver running on the PNA PC is responsible for capturing the 3D data, monitoring and control of the device.

![Diagram](image)

**Figure 20: Illustration of the Coda Octopus data flow**

Depending on the mission requirements, the Echoscope Coda Octopus can be mounted on the AUV/HROV or on board the MV (Figure 21). The Echoscope Coda Octopus will be mounted in the MV when testing the mining process without the help of the support AUV/HROV, and mounted in the AUV/HROV, during some field tests to assess the usability and advantages of using the AUV to provide different perspectives of the dredging head and of the mining process, to improve the realtime 3D map. In this last scenario the Echoscope Coda Octopus will be mounted and tested in AUV/HROV in the place of the M3 sonar.

![Image](image)

**Figure 21: Integration of the Echoscope Coda Octopus system into the MV.**
4 Evaluation

The developed system is going to be deployed and tested during the upcoming mining trials at a china clay pit near Lee Moor in Devon, England. During the trials metrics will be gathered to quantify the viability of the system for the planned tasks. The experiences of these trials and operator feedback will then be used to further improve the system for the second mining trial in the ¡VAMOS! Project.

5 Conclusions

In this report we described the implementation of the multi-sensor navigation system and the integration of all the subsystems on the MV, LARV, AUV/HROV and CC. The subsystems were tested in both lab and field environments. Data from these subsystems feed the 3D terrain modelling system, presented in deliverable D4.1, and with the virtual reality scene of the ¡VAMOS! Human Machine Interface. Using this together with CAD models of the mining system we can provide a useful situational overview in order to assist the pilots of the equipment.

But the full system validation of the Multi sensor Navigation system in a real environment will be only possible in the first field trial test at Lee Moor, when integrated with the ¡VAMOS! MV, LARV and CC and after deployment in an underwater open pit mine environment.