This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement number: 642477

Project acronym: ¡VAMOS!
Project title: ¡Viable Alternative Mine Operating System!
Funding Scheme: Collaborative project

D4.3: Mining Supervision System v3 (Final)

Due date of deliverable: 31/07/2017
Actual submission date: 31/07/2017
Start date of project: 01/02/2015
Duration: 42 Months

Organisation name of lead contractor for this deliverable: BMT
Participating: BMT, ZfT

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<td>01-08-17</td>
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</table>

| Number of pages: | 23 |
| Number of annexes: |   |
Content

1 EXECUTIVE SUMMARY .................................................................................................................................................. 5

2 INTRODUCTION .................................................................................................................................................................. 6

2.1 THE ¡VAMOS! PROJECT ...................................................................................................................................................... 6

2.2 DELIVERABLE D4.3 MINING MANAGEMENT INFORMATION SYSTEM .................................................................................. 7

2.2.1 Objectives .......................................................................................................................................................................... 7

2.2.2 Approach ........................................................................................................................................................................... 7

2.2.3 Timetable ........................................................................................................................................................................... 8

3 SYSTEM COMPONENTS .......................................................................................................................................................... 9

3.1 MINING VEHICLE HMI .......................................................................................................................................................... 9

3.1.1 Mining Vehicle HMI Description ...................................................................................................................................... 9

3.1.2 Mining Vehicle HMI in the overall design ............................................................................................................................ 14

3.1.3 Mining Vehicle HMI development .................................................................................................................................... 15

3.1.4 Mining Vehicle HMI testing ............................................................................................................................................... 16

3.1.5 Mining Vehicle HMI integration & commissioning ........................................................................................................... 18

3.1.6 Mining Vehicle HMI evaluation ........................................................................................................................................ 18

3.1.7 Mining Vehicle HMI Conclusions .................................................................................................................................. 18

3.2 LAUNCH AND RECOVERY VEHICLE HMI ............................................................................................................................ 19

3.2.1 Launch and Recovery Vehicle HMI Description ................................................................................................................ 19

3.2.2 Launch and Recovery Vehicle HMI in the overall design ................................................................................................... 22

3.2.3 Launch and Recovery Vehicle HMI development ............................................................................................................ 22

3.2.4 Launch and Recovery Vehicle HMI testing ........................................................................................................................ 22

3.2.5 Launch and Recovery Vehicle HMI integration & commissioning .................................................................................... 22

3.2.6 Launch and Recovery Vehicle HMI evaluation .................................................................................................................. 22

3.2.7 Launch and Recovery Vehicle HMI Conclusions .............................................................................................................. 23

List of tables:
Table 1: Deliverable Timetable ...................................................................................................................................................... 8
Table 2: Data Protocol Description ............................................................................................................................................... 14
Table 3: Real-Time Data Description ....................................................................................................................................... 15

List of figures:
Figure 1: MV HMI Top & Side Views ........................................................................................................................................ 10
Figure 2: MV HMI Top & Cutter Profiler Views ........................................................................................................................ 10
Figure 3: MV HMI Cutter Control View .................................................................................................................................. 11
Figure 4: Potential Vantage Points for the Cutter Monitoring and Control View .......................................................................... 12
Figure 5: MV HMI Mine Plan and Macro Awareness Example ................................................................................................ 13
Figure 6: Vamos Partner Data Interfaces ................................................................................................................................ 14
Figure 7: Visualization of the miner’s cut path ............................................................................................................................ 15
Figure 7: Comparison of Scan of Physical Miner and Virtual Miner Model .................................................................................. 16
Figure 9: Integration of Bejanca Bathymetric Data into the Simulator ........................................................................................ 17
Figure 10: LARV Launch Procedure ......................................................................................................................................... 19
Figure 11: LARV HMI Winch Control View .............................................................................................................................. 20
Figure 12: LARV HMI 3D Winch Control View ........................................................................................................................ 21
Figure 13: LARV HMI Miner Lowering Desired Vs. Projected Overlays .................................................................................... 21
List of Abbreviations:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full description</th>
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<tbody>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>HROV</td>
<td>Hybrid Remotely Operated Vehicle</td>
</tr>
<tr>
<td>iUSBL</td>
<td>inverted Ultra Short Baseline</td>
</tr>
<tr>
<td>LARV</td>
<td>Launch &amp; Recovery Vessel</td>
</tr>
<tr>
<td>MV</td>
<td>Mining Vehicle</td>
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<tr>
<td>SLS</td>
<td>Structured Light System</td>
</tr>
<tr>
<td>LIBS</td>
<td>Laser Induced Breakdown Spectroscopy</td>
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<tr>
<td>VR</td>
<td>Virtual Reality</td>
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<td>PNAS</td>
<td>Positioning Navigation and Awareness</td>
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<td>TCP/IP</td>
<td>Transmission Control Protocol/Internet Protocol</td>
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<td>User Datagram Protocol</td>
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<td>DDS</td>
<td>Data Distribution Service</td>
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1 Executive Summary

The purpose of this document is to present the status of the deliverable D4.3 – Mining Supervision 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!. This comprises two key components. The first is the Human Machine Interface (HMI) for assisting the operator with remote awareness and control of the mining vehicle. The second is the equivalent system for the Launch and Recovery Vehicle (LARV). For both components, the novel central element of the approach was 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 will be dynamically adjusted so that it faithfully replicates the real operation at all times. This model will be 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. A simulator was created to assist the development of the relevant information displays for different stages of the mining process. This, in combination with testing of data interfaces with other consortium members, means that both key components have been developed to a point of viable demonstration of capability. However, they will continue to be iteratively improved, both to ensure that it is compliant with any changes in the data inputs, and accommodates desired changes to the information displays.
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:

1. Develop a prototype underwater, remotely controlled, mining machine with associated launch and recovery equipment
2. Enhance currently available underwater sensing, spatial awareness, navigational and positioning technology
3. Provide an integrated solution for efficient Real-time Monitoring of Environmental Impact
4. 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
5. Evaluate the productivity and cost of operation to enable mineability and economic reassessment of the EU's mineral resources.
6. 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.
7. Contribute to the social acceptance of the new extraction technique via public demonstrations in EU regions.
2.2 Deliverable D4.3 Mining Supervision System

2.2.1 Objectives
The purpose of this document is to present deliverable D4.3 – Mining Supervision System, as specified in Grant Agreement, 642477, ANNEX 1 (part A), Work Package 4. This consists of a demonstrator prototype for a HMI and mine information system for the control of the MV, the LARV and visualization of material grade, environmental parameters, mine plan and other environmental information.

More specifically, this deliverable will address the creation of a virtual reality system which will assist or enable the following features:

- HMI system for the operation of the MV
- HMI system for the operation of the LARV
- System for visualizing the output of the LIBS grade control system, environmental sensors and adherence to the mine plan in a 3-dimensional environment
- The specification and preliminary testing of the data interfaces required for the real-time visualization of the operation using the 3D virtual reality system.

2.2.2 Approach
The central element of the proposed HMI 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 HROV, the support barge, the riser system, and any other relevant static structures. This model will be dynamically adjusted so that it faithfully replicates the real operation at all times. This model will then be used to visualize all aspects of the operation and to deliver a range of functionalities. This novel method presents several advantages over traditional means of underwater remote operation (whereby operators view the raw output of underwater cameras and other sensors), these being:

- **Viewpoint Flexibility:**
  Once all the information is integrated into the VR environment, user/s can position and move their viewpoint to any desired location and are not affected by the field of view of the specific sensors used. (For an example see Figure 4). This can also be used in combination with knowledge of the operation to automatically position the operator’s viewpoint at an optimal position for each phase of operation.

- **Information Overlays:**
  The VR approach enables the overlaying of relevant 2 and 3-dimensional information to give the operator meta-awareness beyond the mere position and orientation of various components. In the case of ¡VAMOS!, this information can be the intended cut path, force vector of a LARV positioning winch, deviation from intended miner landing position and more. For an example refer to figures 1, 2, 5, 7, 11, 12 & 13. Another capability offered by this approach is the ability to render specific geometry transparently (or not at all), allowing visualization options that are unavailable to traditional sensors (refer Figure 4).
• Turbidity:
With the enclosed water environments that are the focus of the ¡VAMOS! project, it is expected that the cutter head of the mining vehicle shall agitate silt particulates and increase the turbidity of the water. These plumes of particulates will not be transported by current and tidal flows as would normally occur in an open water environment and could render optical based sensors such as cameras of little use. The fact that the VR model shall receive data from an array of sensors including acoustic-based sensors should mean that it can provide a clear picture of the mining environment regardless of the turbidity.

• Analysis and Automation:
The fact that all the input data is synthesized into a computer interrogatable environment has two key advantages when it comes to analysis and automation. Firstly, key parameters can be logged which allows for retrospective analysis of the performance of the system over time and allows comparison between different shifts, operators, material types and more. Secondly, the system enables operator assisted driving and potentially full driverless operation. The fact that all position navigation and awareness information is in a computer interrogatable form dramatically reduces the effort required to allow an autonomous system to safely and accurately pilot the mining vehicle and LARV.

• Collision Avoidance:
Once all fixed and moving assets are loaded into the VR environment, the calculation of closest approach distances for collision becomes a simple process. Simple algorithms enable the instantaneous checking for collision of all parts of a complex piece of machinery against all other moving machinery and the static terrain, see figures 1 & 2 for an example.

In order to advance the development of this approach, a simulated virtual environment has been created to evaluate the effectiveness of visual outputs and the data interfaces that will be required for the final implementation.

This document provides details on the HMI designs, interfaces with other subsystems and reports on the mining supervision system. The overview of the work plan and roadmap of this deliverable is shown below.

### 2.2.3 Timetable

*Table 1: Deliverable Timetable*

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<th>Scope in deliverable</th>
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<td>24</td>
<td>Updated status</td>
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<td>30</td>
<td>Software prototype</td>
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8
3 System Components

3.1 Mining Vehicle HMI

3.1.1 Mining Vehicle HMI Description

The Mining Vehicle HMI component of the Mining Supervision System is a predominantly software system that assists the operator with remote awareness and control of the mining vehicle. It does this through the creation of a 3D Virtual Reality (VR) model of the mining operation.

The initial MV HMI is split into two separate displays. One primarily associated with the movement and navigation of the MV and the other associated the monitoring and control of the cutting process.

3.1.1.1 Mining Vehicle Navigation

The main MV navigation display consists of an orthographic top and side view to allow for easy assessment of the navigation of the MV in the horizontal and vertical plane. The top view shows the MV in plan and has two dashed semi-transparent lines to mark the edges of the current trench and a continuous semi-transparent line to define the center of the current trench with the purple trace emanating from the center of the lift point to indicate MV adherence to intended course.

The side view presents the MV in profile and shows a thick yellow line to indicate the intended bottom of the current trench. In the case of a ramp-down the line would show the intended profile of the ramp cut. There is also a thick red line to show the cutter head’s relative distance to this desired height. Shown in both top and side views there are two collision detection indicators showing the closest approach distances of the miner body to the trench wall or other potential collision dangers and the closest approach distance of the cutter head to the terrain to assist in the engagement with the dig face.

To the right of these orthographic views there is a GUI showing roll and pitch indicators and numerical and simple graphical representation of the collision distances corresponding to the indicators represented in the orthographic views. A snapshot of this interface is shown in Figure 1.
Alternatively, once the MV has traveled close to the dig face the side orthographic view can be switched to a cutter profile view which allows an isolated view of the engagement of the cutter on the dig face. A snapshot of this view is shown in Figure 2.
3.1.1.2 **Mining Vehicle Cutter Monitoring and Control**

The main cutter monitoring and control display has one large perspective view, which can be set to a variety of viewpoints in order to gain improved perspective and can also be set to a freely movable viewpoint. To the right of this main view is a GUI which contains:

- An instantaneous torque readout
- A time history graph of net cutting rate
- An instantaneous numerical readout of cutter speed
- A compound dial that shows current slew position and rate
- A compound dial that shows luff position, cutter head height and difference from last cut

A representative example from the simulator of this cutter monitoring and control display is shown in Figure 3.

Figure 3: MV HMI Cutter Control View
The main perspective view can be set to one of three preset potential views or a free-fly view that can be moved to any desired perspective. The three preset views and an example of an available free-fly view is shown in Figure 4. The left and right cutter views are fixed to the MV body and are orientated to the left and right sides of the MV to observe the cutter head whilst it is on that side. The central cutter view is fixed to the machine arm and slew and luffs as the cutter progresses in order to give a close view of the cutter head at all times.

*Figure 4: Potential Vantage Points for the Cutter Monitoring and Control View*
3.1.1.3 Mine Plan and Macro Awareness Views

If a sense of macro mine plan adherence or other whole of scenario perspectives is required, either of both of the MV navigation and cutter monitoring and control screens can be switched to show the whole scenario in plan and 3D perspective views respectively. An example of the design of these is shown in the figure below. This same environment can be used to visualize 3D information from the LIBS grade control system and key environmental parameters.

![Figure 5: MV HMI Mine Plan and Macro Awareness Example](image-url)
3.1.2 Mining Vehicle HMI in the overall design

Given that both key components of the Mining Supervision System, that being the Mining Vehicle HMI and the Launch and Recovery Vehicle HMI, have similar interfaces with the rest of the ¡VAMOS! system, the information pertinent to both components shall be presented in this section.

The Mining Supervision System is predominantly a software system. It shall be run from a processor housed in the server rack in the control cabin. This processor shall be network enabled and shall receive the relevant real-time data from a variety of sources. The following figure shows the relevant real-time data interfaces.

![Figure 6: ¡VAMOS! Partner Data Interfaces](image)

A summary of the data protocols indicated in the figure above is given in the table below:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Data Protocol Name</th>
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<td>TCP/IP</td>
<td>Transmission Control Protocol/Internet Protocol</td>
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<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>DDS</td>
<td>Data Distribution Service</td>
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Table 2: Data Protocol Description
The data that will be transferred via the interfaces indicated in Figure 6 are summarized in the table below:

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<td>Terrain height map or mesh</td>
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<tr>
<td>MV Position and Orientation</td>
<td>INESC</td>
<td>Cartesian position and orientation in world coordinates</td>
</tr>
<tr>
<td>HROV Position and Orientation</td>
<td>INESC</td>
<td>Cartesian position and orientation in world coordinates</td>
</tr>
<tr>
<td>LARV Position and Orientation</td>
<td>Damen/INESC</td>
<td>Cartesian position and orientation in world coordinates</td>
</tr>
<tr>
<td>MV Articulations and Sensor Data</td>
<td>SMD/INESC</td>
<td>Machine Arm Articulations, Hydraulic Pressures, PLC states, etc.</td>
</tr>
<tr>
<td>LARV Articulations and Sensor Data</td>
<td>Damen/INESC</td>
<td>Winch positions, speeds and tensions (if applicable), PLC states, etc.</td>
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</tbody>
</table>

3.1.3 Mining Vehicle HMI development
The main strategy for the development of the Mining Vehicle HMI was through the production and distribution of a simulator of the mining vehicle. This allowed users to have an experience of driving the mining vehicle and allowed them to ascertain what information displays were useful at different stages of the operation. One of the features that was developed with the input of SMD was the visualization of a predesigned cut path, as shown in the figure below:
As the design of the mining vehicle advanced the updated miner concept was loaded into the simulator. At one stage a survey laser scanner was used to take a scan of the build progress of the miner. The results of this laser scan were loaded into the simulator software and enabled a comparison of the virtual models that will be used in the HMI against the physical geometry of the miner. The results of this comparison are shown in the Figure 8.

![Figure 8: Comparison of Scan of Physical Miner and Virtual Miner Model](image)

3.1.4 Mining Vehicle HMI testing

The majority of testing relating to the Mining Vehicle HMI was undertaken by way of the simulator. However, there were a number other tests that were done of the data interfaces. This involved one of the consortium members creating a “dummy” application and sending to another consortium member for interfacing testing. This “dummy” application would attempt to establish a connection and send or receive simulated data. This process allowed the confirmation of functioning data interfaces prior to the mining trials. Two examples of this were Zft creating a dummy application that sent example terrain information and INESC creating a dummy application that sent example position and navigation information.

Another significant aspect of testing was the collection of bathymetric data from mine sites by INESC. The data that was collected at the Bejanca mine site was processed by Zft and loaded into the simulator software as a test of the principals of this process. The results of this can be seen in Figure 9.
Figure 9: Integration of Bejanca Bathymetric Data into the Simulator
3.1.5 Mining Vehicle HMI integration & commissioning

As the majority of this system is software minimal hardware integration is required. The processor that shall run the software has already been installed in the server rack in the control cabin. The software interfaces shall need further testing as each of the consortium member’s software systems are refined. The presence of the processor in the control cabin should allow testing on a hardware platform that is as similar as possible to the one that shall be used for the mining trials.

3.1.6 Mining Vehicle HMI evaluation

Whilst there has been feedback from the simulator it is strongly expected that the usage of the system during the mining trials shall illuminate a variety of ways the information on the displays can be more appropriately tailored to match different stages of the operation. Fortunately, the software is flexible and should be able to be changed in response to this feedback either during the first trial or between the first and second trials. In terms of evaluation and validation of the VR approach the main determining factor for that shall be whether the operators preferentially use it over the raw input from the cameras and other sensors and whether it can provide them with insights that are not available from the raw sensor input.

3.1.7 Mining Vehicle HMI Conclusions

In conclusion, the Mining Vehicle HMI has been developed to a point of viable demonstration of capability but will continue to be iteratively improved both to ensure that it is compliant with any changes in the data inputs and desired changes to the information displays.
3.2 Launch and Recovery Vehicle HMI

3.2.1 Launch and Recovery Vehicle HMI Description

In a similar vein to the MV HMI there are two main displays for the control of the LARV, one primarily associated with the navigation of the LARV and another associated with managing the process of lowering the miner. There is a sequential procedure established in the simulator for the launch process which will first be summarized.

3.2.1.1 LARV Launch Procedure

The launch procedure (as currently represented in the simulator) has several sequential steps, these being:

1. Selection of desired miner position
2. Navigation of LARV to corresponding desired launch position
3. Commencement of lowering
4. Final realignment and landing

These steps are shown in the Figure 10.

![Figure 10: LARV Launch Procedure](image)

Selection of Desired Miner Position  Navigation of LARV

Final Realignment and Landing  Commencement of Lowering
3.2.1.2 LARV Navigation Display
Throughout this process this LARV navigation display maintains an orthographic top view. The semitransparent green representation of the LARV represents the desired LARV position and adjusts to be aligned directly above the desired MV position. This alignment is of the winch point of the miner with desired winch point. The yaw of the miner is controlled during lowering via the yaw control thruster on the frame of the MV. The arrows represent the force vectors applied by each of the adjustment winches, the size and color of the arrows are scaled by magnitude and the arrows orientate to show direction. The GUI on the right shows the desired speed, tension, actual speed and payout of the three winches and the separation distance and rate of change between the actual LARV position and desired LARV position. The red rectangle in the top view and the orange line around winch numbers indicates the current winch which is being controlled.

![LARV HMI Winch Control View](image)

3.2.1.3 Lowering Process Management Display
The other display for the LARV control is primarily focused on the management of the lowering process. It is a 3D perspective view in a constrained orbit around a central object that can be moved to be focused on the desired MV, desired LARV, MV and LARV. When focused on the LARV it can also display the force vectors and other guides associated with the navigation of the LARV (see the Figure 12 below).
Once the lowering has progressed to near the desired landing position another guide can be enabled which shows the projected location of the MV on the ground if it continued to be lowered on its current course. This allows for early warning of problems associated with lowering the MV down on to the edge of a trench and other dangers associated with the lowering process. This feature is shown in Figure 13 below.
3.2.2 Launch and Recovery Vehicle HMI in the overall design

Given that both key components of the Mining Supervision System, that being the Mining Vehicle HMI and the Launch and Recovery Vehicle HMI, have similar interfaces with the rest of the ¡VAMOS! system the information pertinent to both components has been presented in section 3.1.2.

3.2.3 Launch and Recovery Vehicle HMI development

In a similar vein to the MV the majority of the development of the LARV HMI was undertaken utilizing the simulator. This enabled developers to appreciate what information would be pertinent to different stages of the operation.

3.2.4 Launch and Recovery Vehicle HMI testing

Also in a similar way to the MV the majority of the testing relating the LARV HMI was undertaken by way of the simulator. However, there were a number of other tests that were done of the data interfaces. This involved one of the consortium members creating a “dummy” application and sending to another consortium member for interfacing testing. This “dummy” application would attempt to establish a connection and send or receive simulated data. This process allowed the confirmation of functioning data interfaces prior to the mining trials. Two examples of this were Zft creating a dummy application that sent example terrain information and INESC creating a dummy application that sent example position and navigation information.

3.2.5 Launch and Recovery Vehicle HMI integration & commissioning

As the majority of this system is software minimal hardware integration is required. The processor that shall run the software has already been installed in the server rack in the control cabin. The software interfaces shall need further testing as each of the consortium member’s software systems are refined. The presence of the processor in the control cabin should allow testing on a hardware platform that is as similar as possible to the one that shall be used for the mining trials.

3.2.6 Launch and Recovery Vehicle HMI evaluation

Whilst there has been feedback from the simulator it is strongly expected that the usage of the system during the mining trials shall illuminate a variety of ways the information on the displays can be more appropriately tailored to match different stages of the operation. Fortunately, the software is flexible and should be able to be changed in response to this feedback either during the first trial or between the first and second trials. In terms of evaluation and validation of the VR approach the main determining factor for that shall be whether the operators preferentially use it over the raw input from the cameras and other sensors and whether it can provide them with insights that are not available from the raw sensor input.


3.2.7 Launch and Recovery Vehicle HMI Conclusions

In conclusion, the Launch and Recovery Vehicle HMI has been developed to a point of viable demonstration of capability but will continue to be iteratively improved both to ensure that it is compliant with any changes in the data inputs and desired changes to the information displays. It is expected that the testing and integration will be finish state prior to the commencement of mining trials and any changes after that point will be minor and optional.