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List of Abbreviations:

Acronym	Full description
AUV	Autonomous Underwater Vehicle
DDS	Data Distribution Service
DEM	Digital Elevation Model
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human Machine Interface
INS	Inertial Navigation System
LARV	Launch & Recovery Vessel
MV	Mining Vehicle
NTP	Network Time Protocol
PPS	Pulse Per Second
ROS	Robot Operating System
RTK	Real Time Kinematic
SDF	Signed Distance Function
SLAM	Simultaneous Localization and Mapping
SLS	Structure Light System
TSDF	Truncated Signed Distance Function
VR	Virtual Reality

1 Executive Summary

The purpose of this document is to present the status of the deliverable D4.1 – Real Time Mining Modelling as specified in Grant Agreement, 642477, ANNEX 1 (part A), Work Package 4; consisting of a prototype demonstrator for signed distance function based environment modelling in 3D. This provides online 3D reconstruction to create a representation of the mining environment for visualization and advanced spatial awareness.

The challenge in tele-operating a large underwater mining vehicle is that there is no direct intervisibility, which makes precise control difficult. The perception data of the mining vehicle can only be communicated via a computer interface. One part of these efforts in the ¡VAMOS! project to enhance situational awareness of the operator is the real time mining modelling 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 modelling 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 truncated signed distance function voxel map and sensor models were developed to integrate measurements taken with varying accuracy and noise properties. 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. The resulting 3D terrain map is presented in a virtual reality to the operator via the Human Machine Interface developed in T4.1.3. This map is then augmented with information from other subsystems, such as positioning information, machine parameters, and measurements of the extracted slurry, and presented to the operator in a consistent environment.

The developed approach has so far been validated on test data sets captured in a submerged mine using parts of the ¡VAMOS! surveying equipment and will be tested during the upcoming mining field trials. The expected benefits of this approach in the ¡VAMOS! project are that the human operators can gain a better situational overview and understanding of the mining operations which assists remote control. Additionally, a full 3D model of the operations is valuable to monitor effectively what is happening below the water surface and communicate the status of mining operations. Moreover, it allows the use of a smaller and cheaper sensor kit since only the areas where change is expected need to be monitored regularly with surveying equipment while the full context of the mine site can still be visualized to the human operator.

The development work and associated field testing leads us to believe that an accurate situational model can be created to enable the pilots of the equipment to operate efficiently. The work done towards achieving this is described further in the main body of this report.

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 mine-ability 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 D4.1 Real Time Mining Modelling

2.2.1 Objectives

The purpose of this document is to present the status of the deliverable D4.1 – Real Time Mining Modelling as specified in Grant Agreement, 642477, ANNEX 1 (part A), Work Package 4; consisting of a prototype demonstrator for signed distance function based environment modelling in 3D.

More specifically, this deliverable addresses the development of a 3D mine mapping system which will provide the following features:

- Framework based on signed distance functions for representing changing environments
- Online reconstruction of the mining environment in 3D
- Interfaces for the visualization of the 3D map in the virtual reality system to provide advanced spatial awareness for the operation of the mining vehicle
- Interpretation and augmentation of the created 3D maps

2.2.2 Approach

The real time mine modelling system takes as an input the raw sensor measurements, calibration information and filtered positioning information of the navigation system. This information is used to transform all point measurements of all sensors to a global reference frame. The resulting point cloud is further improved using simultaneous localization and mapping (SLAM) techniques. For multi-sensor and multi-view data integration signed distance function (SDF) based mapping is employed. SDF voxel maps represent the surfaces implicitly by storing in each voxel cell the signed distance to the closest surface. A SDF map is a beneficial surface representation because noisy measurements are smoothed over multiple observations. Moreover, by fusing 3D point measurements into a consistent model only the model of the mine needs to be kept in memory at any time, while the full history of all scans can be discarded or only logged to disk.

This document provides details on the design, algorithms, employed models of the real time mine modelling system and interfaces with other subsystems.

2.2.3 Timetable

The table below provide the timetable in project schedule months for the development of the Real Time modelling component of the ¡VAMOS! system.

Figure 1: Timetable

Release month	Scope in deliverable
12	Development status
24	Updated status
30	Software prototype

3 Real Time Mine Modelling System

This section gives a more detailed description on the approaches that are employed in real time mine modelling in the ¡VAMOS! project. Section 3.1 and 3.2 provide an overview of how the sensor measurements are transformed to a global coordinate system and how the mine mapping works with the calibration, synchronization, registration and SLAM algorithms developed in the project. In Section 3.3 the rational supporting why SDF based models are used for the mine modelling is explained and what properties and advantages this method provides. Furthermore, implemented design decisions on data structures and how large-scale mine maps can be handled are reported. Section 3.4 gives a brief overview on the interfaces between the mine mapping system and other subsystems, such as the HMI, positioning, navigation and sensor systems. Some details are explained in Section 3.5 on how the SDF maps can be rendered in the virtual reality system developed in T4.1.3.

3.1 Calibration Information of Sensor Systems

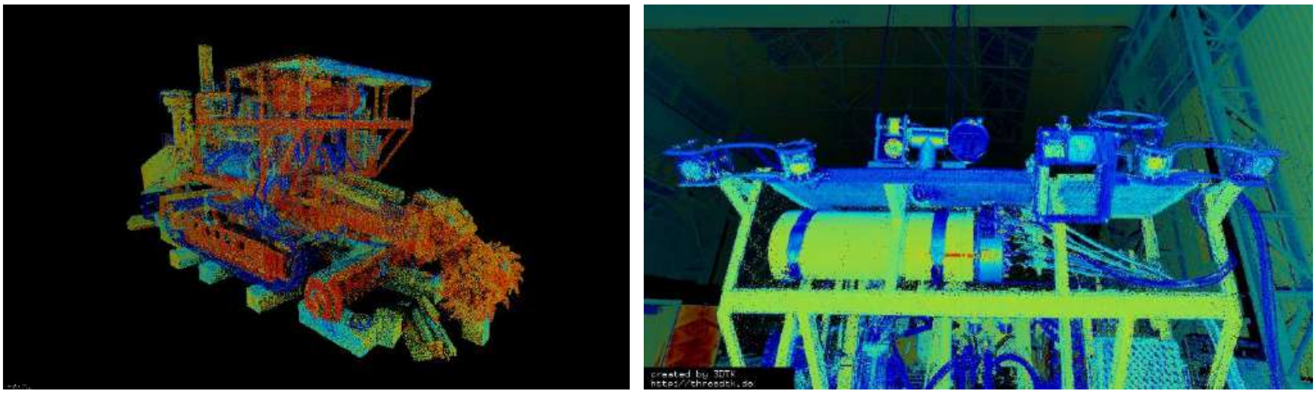
Before the mining trials all sensor systems are individually calibrated at the mine site prior to the deployment of the mining vehicle, such that consistent results can be achieved in spite of varying parameters, such as water conductivity. Moreover, capture timestamps of all sensor measurements are logged and all systems are synchronized to a common time base using network time protocol (NTP) and pulse-per-second (PPS) signals. Details on the calibration and time synchronization of the individual sensor systems can be found in the ¡VAMOS! report on deliverable D4.5 - Registration, Calibration and Synchronization.

In order to reference all 3D point measurements of the perception sensors to a global reference coordinate system and create maps of the environment, we need to know all the mounting positions and orientations of all sensors systems attached to the mining vehicle, AUV and LARV. Traditionally, this can be achieved, for example, using calibration fixtures which are visible by multiple sensors or tachymeter measurements of reference markers placed on the individual sensors.

In the ¡VAMOS! project this is challenging because different sensor modalities are employed and it is costly to design calibration fixtures which are visible, e.g., in optical sensors as well as in sonar sensors. Moreover, considering the large size of the mining vehicle, very large calibration targets would be necessary, such that they are visible in multiple sensors. Therefore, we plan on using a combination of laser scanning and self-calibration techniques for estimating the extrinsic parameters of all sensors mounted on the mining machine relative to the base coordinate system of the vehicle. We create an initial estimate of the sensor poses on land before the mining machine goes into the water using laser scanning. This makes calibration faster and less complicated because access to all sides of the vehicle is easier on land. The second step of refining these initial estimates using self-calibration techniques can be applied in air as well as in the water (with the exception of the acoustic imaging sensors which cannot be operated in air). This potentially also compensates for slight changes in sensor mounting positions due to mechanical stress during deployment of the vehicle.

The concept of creating initial sensor pose estimates using laser scanning is the following. First, we scan the mining vehicle using a terrestrial laser scanner from all sides. We transform these scans into a common reference frame using automatic high-precision 3D point cloud registration techniques. An example point cloud of the mining machine created from multiple scans is shown in Fig. 1(a). Fig. 1(b) depicts a 3D point cloud of the sensor bar mounted to the vehicle. Second, we register models of the individual sensors, which are created from CAD data, to the laser scan of the vehicle. This way we can find the relative pose and orientation of the sensor. An example of this process for the 3D imaging sonar CodaOctopus Echoscope is depicted in Fig. 2. Fig. 2(a-c) show a manual initialization of the sensor pose and Fig. 2(d-f) the optimized result.

The second step of refining these initial estimates can be applied during operation of the vehicle. It is used to improve alignment errors introduced due to errors of the rotational offsets of the sensor poses. This optimization of the calibration parameters is performed in the following way: First, the vehicle with the mounted sensors is moved such that sensor measurements are taken from different vehicle poses. We record the trajectory of the vehicle at the same time using the positioning system and manually verify that we have a good trajectory solution. Then the rotational offset is optimized based on an error measurement which determines point cloud quality similar to the calibration approach of Sheehan et al.[1]. The error measurement is computed by splitting the trajectory into overlapping parts and calculating a point distance error based on closest point correspondences. We find sensor parameters that minimize the error and verify the result on different trajectory segments. More details on this self-calibration approach and examples using data captured in the ¡VAMOS! project can be found in the report on deliverable D4.5 - Registration, Calibration and Synchronization.



(a) (b)

Figure 2: 3D laser scan of the mining machine (a) and the sensor bar mounted to the vehicle (b). The point clouds are colored by the reflectance values of the laser measurements.

[1] Sheehan, M., Harrison, A., and Newman, P. (2012). **Self-calibration for a 3D laser**. The International Journal of Robotics Research, 31(5), 675–687.

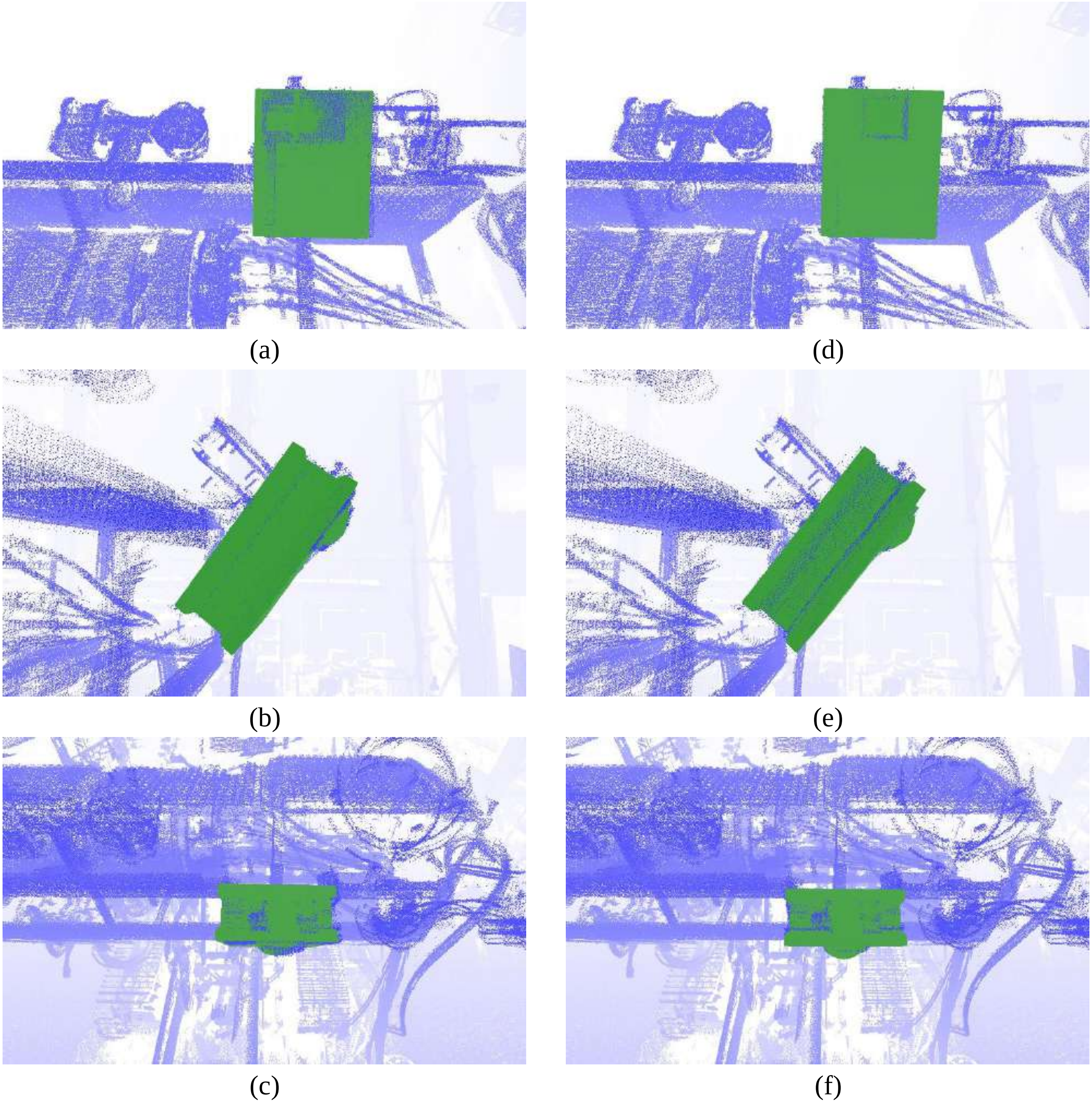


Figure 3: 3D laser scan of the mining machine in blue and model of the CodaOctops Echoscope 3D sonar created from CAD data in green. Initial alignment is show in (a-c) and the final optimized pose in (d-f).

3.2 Mine Mapping

Using the sensor calibration information and the pose measurements of the positioning system all 3D point measurements can be transformed to a global reference frame. Details on the acoustic positioning system can be found in the ¡VAMOS! deliverable D4.4 - Multi-sensor navigation system.

When building a 3D model from a moving vehicle, such as the mining vehicle or HROV, a common problem is that over time sensor measurements and model drift apart from each other and errors accumulate. In the pre-survey we address this problem by applying continuous-time SLAM algorithms, which optimize point cloud consistency globally, i.e., for all the sensor measurements of the complete map. This allows us to create an initial mine model with good consistency and quality. Details on the employed continuous-time SLAM algorithms and results from field tests carried out in the ¡VAMOS! project can be found in the report on deliverable D4.6 - Fusion and SLAM solution. We can also apply this approach to process surveys carried out using the AUV to update the map of the complete mine. However, it is not feasible to apply these SLAM algorithms globally for the real-time processing of all data since they are computationally expensive if a large number of scans need to be processed.

Since a valid mine model from the pre-survey already exists we can use this model to minimize drift for the real-time processing. We do this by registering new sensor data with the established mine model. Since this requires only finding a registration between the sensor scan and the model we can compute this in real time. By always computing this alignment between sensor observations and the model accumulated errors can be kept small.

Another issue is that we always want to build the mine model from the best available terrain measurements. For example, we do not want to degrade high resolution, high quality map data gathered, e.g., with the structured light sensors of the AUV, with lower resolution data, e.g., from multi-beam sonar, captured later in time. We can address this problem partially in the weighting scheme of different sensor measurements described in Section 3.3.

3.3 Signed Distance Function Mine Modelling

For integrating measurements from multiple sensors and different views we choose to employ SDF based mapping. SDF voxel maps represent the surfaces implicitly by storing in each voxel cell the signed distance to the closest surface. Typically, the signed distance is only stored in a narrow band around the surfaces, which is referred to as a truncated signed distance function (TSDF). This representation became popular in the robotic mapping community with the work of Newcombe et al. on KinectFusion[2] in 2011, which demonstrated excellent real time 3D reconstruction and tracking results. A SDF map is a beneficial surface representation because noisy measurements are smoothed over multiple observations.

We integrate all scans into a SDF voxel model based on the optimized poses computed by the registration or SLAM solution. The signed distance measurement $d(v)$ for a voxel with center v is computed as follows

$$d(v) = m - \|p - v\| \ ,$$

where p is the sensor position and m is the distance measurement of the sensor. Multiple measurements of the same voxel cell are integrated based on a weighting function f. This way noise cancels out over multiple observations. We store in each voxel cell the signed distance $s(v)$ and the weight $w(v)$. To integrate a new measurement $d(v)$ at iteration $k + 1$ we compute the weighted average

$$s(v)_{k+1} = \frac{w_k(v)s_k(v) + f d_{k+1}(v)}{w_k(v) + f} \ ,$$

[2] R. A. Newcombe, A. J. Davison, S. Izadi, P. Kohli, O. Hilliges, J. Shotton, D. Molyneaux, S. Hodges, D. Kim, and A. Fitzgibbon. **KinectFusion: Real-time Dense Surface Mapping and Tracking**. In: Proceedings of the 10th IEEE International Symposium on Mixed and Augmented |Reality (ISMA 2011), pp. 127-136, 2011.

where f is a weight assigned to the new measurement. The signed distance is truncated to the interval $[s_{min}; s_{max}]$. Since we do not have an accurate noise model of the sonar sensor, uniform weights ($f = 1$) are employed. The weight is updated by:

$$w_{k+1} = \min(w_k(v) + f, w_{max}) \ ,$$

where w_{max} is the maximum weight.

SDF-based mapping is not completely robust to coarse outliers. Noisy surfaces are only smoothed if the individual measurements lie within a certain band, which is determined by the penetration depths D_{min} and D_{max} of the TSDF. Underwater sonar sensors typically exhibit a number of coarse outliers. Measurement points that lie outside the truncation thresholds are integrated as additional surfaces. To address this problem, we choose a large truncation threshold. This limits the minimum thickness of objects that can be represented by the SDF model. However, in the particular case of a submerged inland mine this is not an issue because we only want to represent a single surface of the mine floor. To remove erroneous integrated surfaces we filter the SDF voxels based on the weight. This is based on the assumption that voxels representing real surfaces carry a higher weight, i.e., are observed more often, compared to voxels filled from measurement outliers.

For modelling the mine we choose a fine voxel resolution, e.g., 10cm. This means the TSDF space of the entire mine has a size in the order of a billion voxels. In order to store large maps with low memory consumption we need to encode free space efficiently. Different techniques to do this have been proposed, such as voxel hashing or octree data structures. For the real-time mine mapping system, we use a B-tree based data structure[3] to store the complete sparse TSDF grid. The tree has constant depth, which allows constant time local and random traversals. We use a three-level tree with branching factors decreasing closer to the leaves.

To integrate the multi-beam data in the TSDF we follow the generalized sensor fusion approach proposed by May et al.[4]. For each sensor system, we create a model based on a back projection function. For example, we model the multi-beam sonar as a polar line sensor with a certain beam width. Individual voxel cells within measurement range are then updated based on back projection using this sensor model.

3.4 Interfaces

In order to enable easy integration sensor drivers are abstracted using the widely adopted robot operating system (ROS). Data exchange between the positioning, navigation, sensor and mine modelling system is based on either direct communication using ROS messages or the Data Distribution Service for real time systems (DDS) middleware. The terrain data is transferred to the HMI virtual reality system using a custom specified network protocol. The interfaces were tested using dummy applications which were shared between the partners or captured data logs. This is expected to easily facilitate the final integration during the mining trials.

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[3] Museth, K. (2013). **VDB: High-resolution sparse volumes with dynamic topology**. ACM Transactions on Graphics, 32(3), 27.

[4] May, S., Koch, P., Koch, R., Merkl, C., Pfitzner, C., and Nüchter, A. (2014). **A generalized 2D and 3D multi-sensor data integration approach based on signed distance functions for multi-modal robotic mapping**. In 19th Int. Workshop on Vision, Modeling and Visualization, 95–102.

3.5 Visualization of the Mine Model in the HMI Virtual Reality System

For rendering a signed distance function 3D map there are two options. One is direct rendering using ray tracing. The other is extracting a mesh from the SDF voxel grid, e.g., using the marching cubes algorithm and rendering this surface mesh. In ¡VAMOS! large areas of the map will not change very often. Only the area around the mining vehicle needs to be updated frequently. Therefore, it is less computationally expensive to choose the rendering option using a mesh extracted from the SDF. The mesh can be pre-computed and stored in memory for rendering. Since most of the mesh representing the environment does not change, only a small volume needs to be updated frequently. On the other hand, direct rendering would require ray tracing of the SDF every time the view of the virtual camera changes.

For visualization in the virtual reality system the map is transmitted as a 2.5D digital elevation model (DEM). This height map is stored as raster data. The complete map is broken up into map tiles, representing the terrain data for a small square area. This allows the HMI to load only the part of the map that is currently visible and only mapped areas that changed need to be transferred via network. Moreover, terrain patches that are further away from the virtual camera can be rendered with less resolution to increase rendering performance. An example of terrain data captured in the ¡VAMOS! project rendered in the virtual reality system is depicted in Fig. 3.

Figure 4: Terrain data of the Bejanca mine site integrated into the HMI virtual reality system.

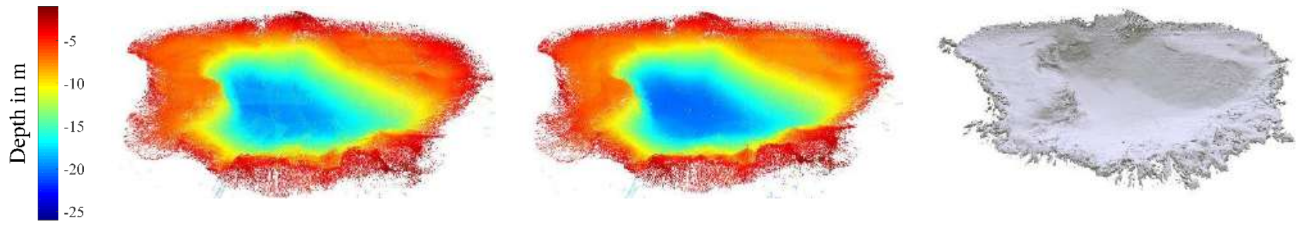
4 Testing on Dataset Captured at the Bejanca Mine Site

To demonstrate the SLAM and mapping algorithms, results on a dataset captured in the Bejanca mine in Portugal using INESC TEC's autonomous surface vehicle ROAZ are depicted in Fig. 4. This dataset consists of 12786 multi-beam sonar scans captured at 10 Hz. It was captured in 22 min and the trajectory is 1567 m long (result of the SLAM solution). For positioning and localization of the vehicle a L1/L2 precision GPS unit with Real Time Kinematic (RTK) differential corrections and a fiber optic based INS were installed on the robotic boat. The employed fiber optic gyro features a very low drift rating of only 0.05deg/h. A high precision localization solution is obtained later by post-processing the raw INS data in combination with the raw GPS data. The post-processing step is performed using the Inertial Explorer software, where all raw GPS observations are processed in RTK and integrated with raw inertial measurements in a tightly coupled manner.

We can see misalignment between multiple passes of the multi-beam sonar in the initial point cloud shown in Fig.4 (a), which is created using the GPS/INS trajectory. Point measurements line up well using the improved trajectory estimate based on continuous-time SLAM visualized in Fig.4 (b). The color encodes the depth. Especially at the bottom of the mine it is visible that the multi-beam measurements are more consistent in the optimised results.

The extracted mesh from the SDF representation using the optimized continuous-time SLAM solution, depicted in Fig. 4(c), exhibits smooth surfaces. Despite the noise of the measurements a smooth surface can be extracted if a sufficient amount of repeated observations are available. The borders of the mine show holes in the mesh. This is a result of the irregular and low point density of the sonar measurements due to limited coverage close to the borders of the mine. Since this is undesirable, we later interpolate the holes for display in the virtual reality system.

Later this underwater model was co-registered with scans from terrestrial laser scanning to create a joint above-the-water and underwater model. The employed surveying equipment is depicted in Fig. 5(a). A precision GNSS unit was mounted to the top of the scanner to reference the scans to geodetic coordinates. Fig. 5(b) shows the resulting point cloud colored by height. In Fig. 5(c) color information from photographs was added to the laser scans captured above-the-water. The underwater data in this image is colored by height.



(a) (b) (c)

Figure 5: Initial (a) and optimized (b) 3D point cloud, surface mesh extracted from signed distance function model (c).

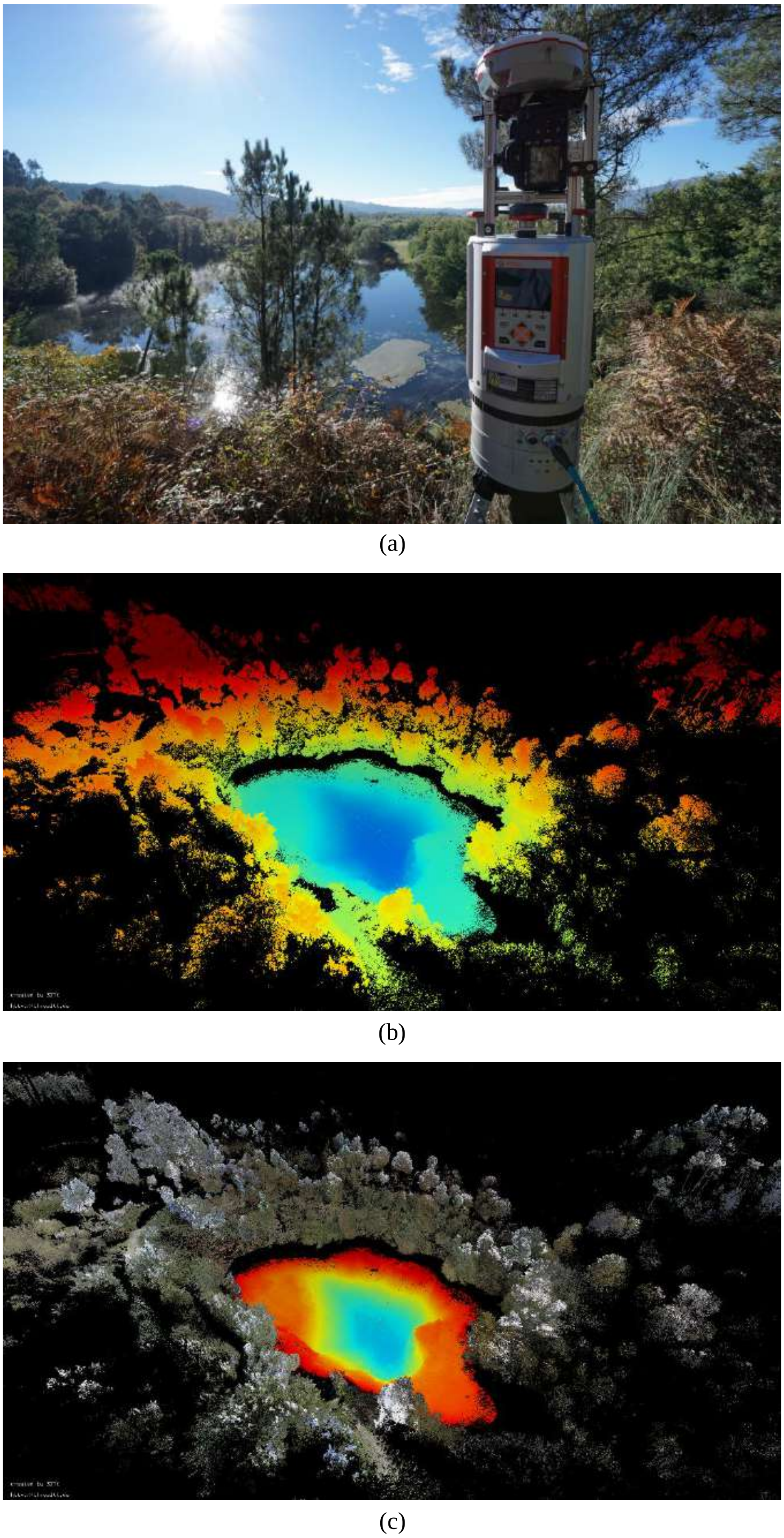


Figure 6: Terrestrial laser scanner with camera and GPS unit at the Bejanca mine site (a), 3D point cloud of the Bejanca mine above-the-water and underwater colored by height (b), and above-the-water data colored using RGB data from camera images (c).

5 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.

6 Conclusions

In this report we showed first field results on creating a detailed 3D terrain model of a submerged inland mine from a multi-beam sonar survey. We have demonstrated that the developed mapping techniques in the ¡VAMOS! project based on signed distance functions are effective for data fusion to create a consistent mine model. Rendering a surface mesh for visualization purposes compared to a point cloud is advantageous because it allows the human operator to see the surfaces and structure more clearly. We have integrated the terrain model into a virtual reality scene of the ¡VAMOS! Human Machine Interface together with CAD models of the mining system to provide a useful situational overview in order to assist remote control.

7 Annex 1 - Related Publications

Two scientific articles describing results of the work in ¡VAMOS! related to the real time mining modelling have been published. Further articles are currently being prepared for submission.

7.1 Published Articles

1. Michael Bleier, André Dias, António Ferreira, John Pidgeon, José Almeida, Eduardo Silva, Klaus Schilling, and Andreas Nüchter. **Signed Distance Function Based Surface Reconstruction of a Submerged Inland Mine Using Continuous-time SLAM**. in Proceedings of the 20th World Congress of the International Federation of Automatic Control (WC ’17), Toulouse, France, July 2017.

2. Michael Bleier and Andreas Nüchter. **Low-cost 3D Laser Scanning in Air or Water Using Self-calibrating Structured Light**, In Proceedings of the 6th ISPRS International Workshop 3DARCH 2017: ”3D Virtual Reconstruction and Visualization of Complex Architectures”, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W3, 105-112, Nafplio, Greece, March 2017.

7.2 Submitted Articles

1. Michael Bleier, André Dias, António Ferreira, John Pidgeon, José Almeida, Eduardo Silva, Klaus Schilling, and Andreas Nüchter. **Real-Time 3D Mine Modelling in the ¡VAMOS! Project**. in Real Time Mining Conference, Amsterdam, Netherlands, October 2017.