Call: HORIZON-CL2-2023-HERITAGE-01

Deliverable No. 2.2

Technical and Business Requirements

Grant Agreement No.:	101132575
Project Title:	Nerites – Systematic autonomous remote surveying of underwater cultural heritage monuments and artefacts using non-destructive, cost-effective and transportable digital solutions.
Contractual Submission Date:	07/2024
Responsible partner:	Alpes Lasers

This project has received funding from the European union’s Horizon Europe research and innovation program under grant agreement No 101132575.

Funded by the European Union

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Deliverable No	**D2.2**
Deliverable name	**Technical and Business Requirements**
Version	**1.0**
Work package No.	2
Lead beneficiary	Alpes Lasers
Type	R – Document, Report
Dissemination level	PU – Public
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Keywords	

Version	**Date**	**Comments**
0.1	09.05.2024	First draft
0.2	18.05.2024	Second draft
0.3	05.06.2024	Partner's contribution
0.4	11.06.2024	Third Draft
0.5	25.06.2024	Draft for internal review
0.6	12.07.2024	Second Draft for internal review
1.0	22.07.2024	Final Draft for submitting

The research leading to these results has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101132575.

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1 Executive Summary

The aim of Deliverable 2.2 of NERITES project is to determine the technical specifications and requirements for the development of the AUV and control center associated with Task 2.2 and Task 2.3. Deliverable D2.2 is followed by the Pilot surveys and use case scenarios definition on Deliverable D2.1 and intends to introduce all the technologies will be used along the implementation of NERITES project. The contributors of this deliverable will focus only on technical specifications and requirements and avoid description of the technologies, which is a task of deliverables in WP3, WP4 and WP5. The objective of Deliverable D2.2 is to provide a framework for the final deliverable of WP2, which will address the systematic degradation assessment of UCH. Deliverable D2.3 will be produced two months after the submission of D2.2 and D2.1. Pilot cases and end user scenarios are described in detail in D2.1 and will be out of scope of the current document. Deliverables and especially technical ones should include the perspective technologies will be used in the WP's will follow. In section 4, all the technologies in NERITES are discussed and introduces the specifications of each technology used. Following the development roadmap of the final product, we firstly discuss the AUV platform specifications regarding the geometry and important requirements partners need to address in their technological development. AUV configuration and size along with the power supply, maneuvering and guidance are important attributes of this document. In the following we discuss the buoy development, and control center specifications, which provide also important information to manage autonomous missions. In the following LIBS and QCL sensors requirements are discussed. This document also introduces mapping, communication analysis and photogrammetry specifications. Finally, degradation protocols will be discussed.

2 Introduction

The development and deployment of autonomous platforms for the remote monitoring and chemical mapping of underwater heritage sites present several significant technological challenges. In the technical specification section, all the technological and industrial requirements are presented by all the participated partners. The methodology that will be followed involves close collaboration between technological partners and responsible for the archaeological sites. Technical directions and geometries for the AUV must be given prior to the mission to ensure the smooth operation of the autonomous systems. In the following several steps highlight the necessary roadmap of the specifications and requirements needed. Directions and ideas were discussed during periodic meeting between the involved partners.

Firstly, the vehicle body and sensors must avoid direct contact with the artefacts to prevent damage. If contact is unavoidable, it must be made using cushioned rubber or by applying minimal pressure. Ensuring this delicate interaction raises concerns about the consistency of LIBS (Laser-Induced Breakdown Spectroscopy) measurements, especially in maintaining a constant distance from the artefacts. Additionally, determining the maximum allowable force and integrating a force-feedback mechanism to automate this process pose substantial engineering challenges.

Positioning the AUV (Autonomous Underwater Vehicle) platform accurately is critical for precise measurements and requires highly sensitive sensors. The exact placement of the LIBS is also crucial, with options including internal housing within the AUV or a hybrid design with internal electronics and external optical components for easier targeting. This decision impacts the design requirements for optical access windows on the AUV hull and necessitates careful consideration of the sensor placement between the propeller and the docking station hardware.

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The docking station itself must be situated, at a distance of 20 to 50 meters from the nearest artefact. This requires precise and stable mooring solutions to ensure the station remains secure and does not disturb the site. Furthermore, the docking station must be robustly anchored to the sea bottom at a depth that minimizes the impact of underwater currents. The stability of the docking station is vital for effective data and power transmission to the AUV.

Energy and communication logistics present additional challenges. The sea-surface buoy must supply continuous energy and maintain communications, but the potential need for supplementary power sources during extended measurement campaigns complicates this requirement. Additionally, establishing a non-intrusive route for power lines from land to the docking station is necessary to avoid interference with the underwater cultural heritage site.

Lastly, the demonstration of precise AUV control is essential for obtaining permits to conduct site demonstrations. This involves showcasing the AUV’s ability to maintain stable hovering, perform safe landings, and navigate accurately using acoustic-based guidance from the docking station as a reference point. Ensuring these capabilities under real-world conditions is a critical step in validating the system’s operational readiness and securing necessary regulatory approvals.

Addressing these technological challenges is crucial for the successful implementation of the autonomous monitoring system and the protection of underwater heritage sites.

3 Scope of Task 2.2 & 2.3

The AUV, with hovering capabilities, has its operational and design parameters specified based on end-user requirements. These parameters may include operational depth, attachment needs, and deployment options. The AUV, along with the BUOY and sub-sea docking station, is deployed to the site by a vessel. The BUOY's requirements, such as anchoring, communication equipment, and connection to the sub-sea docking station, are determined for short or/and long-endurance missions ranging from 10 to 30 days, however the energy requirements of the AUV (including its sensors), docking station, echo sounders, buoys’ equipment, etc. have not been defined and concluded yet. Mission planning, control, and supervision are handled by an onshore or from a vessel control station, which is developed to provide oversight and control of the autonomous platforms (AUV and BUOY), mission planning, asset geolocation relative to the monument site, and real time measurements from the LIBS and QCL sensors. Furthermore, the project outlines the requirements for in-situ sensing and imaging based on the AUV's operational needs for a comprehensive site survey and complete observation and recording by the onshore stations. This task includes establishing the necessary information for reliable subsea in-situ sensing, measurement, and analysis, and determining the communication protocol from sensors to the BUOY and then to the onshore station. Initial evaluations of advanced sensors, such as Photogrammetry (by IHU), LIBS (by LZH), and QCL (by ALPES), are conducted to determine dimensions, weight, connections, options (data/power cables, connectors, pressure housings, etc.), power requirements and data specifications (accuracy, precision, resolution, etc.). The optimal mounting positions for these sensors on the AUV need to be assessed, considering operational requirements. Considering the positioning of the sensing components the developing partner will decide how is going to be the inner geometry of the sensors. For the QCL sensor, the project investigates the most effective and least risky water sampling methods, enabling non-invasive and non-destructive sampling from very close distances to underwater cultural heritage (UCH) artifacts and monuments. The project also evaluates potential camera and imaging equipment, such as multi-beam echo sounders, focusing on the system's underwater application. A preliminary assessment of the computational requirements for the inspection scanning system is performed.

4 Technical Specifications

4.1 AUV platform

General

- Maximum requested operative depth during the project will be: <55 meters.
- Nor the vehicle nor the sensors are allowed to touch the artefacts. An acoustic proximity sensor will be used for granting this fundamental safety aspect.
- The AUV must be able to integrate and carry all the required mission sensors (LIBS, QCL, photogrammetry cameras)
- In the initial testing phase, the AUV will be operated like an ROV in tethered mode. Once the platform will exhibit all the necessary safety features and navigation performance for executing the requested missions in a reliable way, the tether will be removed and the AUV will operate in autonomous mode.

AUV configuration & geometry

- The AUV will be developed starting from the existing X-300 architecture, already exhibiting hovering capabilities
- Given the overall volume of the sensors to be transported, a dual-hull configuration (with dedicated room for equipment in the middle region) is going to be adopted
- The envelope of the frontal section of the AUV must be optimized for facilitating the entrance in the docking station

Energy

- The platform can deliver 2 kW of power (100 Amps 20V) as currently planned on standard batteries. The potential can be increased, possibly via a DC-DC converter.
- The AUV must integrate an underwater connector (very likely an inductive one) enabling the battery recharging while the AUV will be inside the docking station
- A precise power modelling of the AUV is going to be defined by considering the consumption of every equipment and its time of activation during a mission
- The AUV can host extra batteries if needed.

Communications

- The existing WiFi connection of X-300 will be maintained for facilitating the data exchange with the AUV on shore and on the deck, before being deployed in water
- Another radio link (likely through an inductive connector) will enable a high-bandwidth bidirectional data transfer underwater when the AUV will be inside the docking station
- An acoustic link (through an acoustic modem) will also enable a low-bandwidth bidirectional data transfer underwater with the surface buoy when the AUV will be outside the docking station
- During initial testing phases a tether (either a fiber optic or a copper one) will allow a high-bandwidth data transfer also when the AUV will be outside the docking station

Maneuvering & Navigation Requirements

- Precise position control of the AUV is critical, to be able to perform safely the demo inside the actual site.

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- Depth control loop must guarantee an error during navigation lower than 0.2 meter for maintaining a safety distance with objects below the AUV
- Depth control loop must provide an accuracy while getting closer to an object for a LIBS inspection higher than 0.05 meter, with a safety distance echosounder preventing from collision with object
- Horizontal DVL-based odometry (with USBL periodic corrections) must provide an AUV positioning with an error not greater than 2 m
- Horizontal visual-aided navigation must be used for fine positioning and target reaching with an error not greater than 0.2 m
- Acoustic-based navigation will be implemented with acoustic device mounted on the docking station for getting close to it, before finalizing the docking
- The docking finalization will be done by exploiting a mechanical funnel facilitating the AUV entrance in the docking station.
- If the above docking finalization based on the tolerance induced by the mechanical funnel will not exhibit the necessary reliability and repeatability, a visual-aided finalization maneuver could be implemented with visual markers placed on the docking station

Sensors induced Requirements

- QCL does not require specific maneuvers for being operated. For operating properly, the electronics of the QCL must work in a certain range of temperature (5-25 deg), therefore a proper cooling system must be implemented
- The LIBS probe requires to be close to the object to be inspected (10cm-15cm), so the AUV must be able to approach slowly a target to be inspected
- The LIBS probe might become able to autonomously measure its distance from the target through the development of an additional device exploiting a small camera plus a pointwise laser system. If this device will not exhibit enough reliability, a dedicated echosounder will be used for granting that the AUV will not get closer than a safety threshold to any artifacts
- LIBS measurements must be taken both on horizontal objects on the sea bottom (like an anchor) and on vertical surfaces (like a wall). So, the AUV must foresee the possibility of changing the orientation of the probe
- The photogrammetry will mainly require a downward looking stereo camera
- An additional (possibly stereo) forward looking camera will be added for acquiring frontal pictures

4.1 Buoy platform

The buoy is critical to the overall operational concept as it will provide a link between the underwater AUV and the outside world when it is operating over prolonged periods underwater. Batteries and solar panels will be installed on the buoy, to offer energy sufficiency, according to the mission requirements. Communication antennas will also be installed on the buoy to facilitate communication with the control station.

Mooring

The Buoy should be able to be safely moored in both of the selected archaeological sites without compromising the artefacts safety, meaning that the anchoring should be placed in a safe distance and the mooring lines or chains used should avoid touching the seabed near the artifacts. Additional surface or subsurface flotation maybe required to support the mooring weight. Based on weather conditions and operating depth, catenary or inversed catenary moorings could be considered to ensure safe deployment.

Energy system integration

The buoy should accommodate solar panels to harness solar energy. Furthermore, batteries should be installed for energy storage to ensure that the power supply is maintained for continuous operation of both the Buoy's installed sensors and the AUV through the recharging process on the docking station. For this reason, the energy requirements for communication, data exchange and AUV charging should be calculated to size the solar panels and batteries appropriately. Power regulators should be considered to regulate power distribution from solar panels and batteries.

Data Processing Elements

On the buoy a microcontroller should be installed (e.g., Raspberry Pi, Nvidia Jetson AGX Xavier) to manage data flow, execute control algorithms and handle sensors data. It should be equipped with solid state drives (SSDs) or SD cards for local data storage.

Communication Systems

Buoy to onshore: The buoy should integrate LTE or satellite communication antennas for reliable geo-positioning and data transmission to the onshore control center. The data rate should be considered for real time control and monitoring. Encryption and authentication should be implemented to protect data during transmission.

Buoy to docking station

Consideration of using ethernet cables or fiber optics for reliable data transfer (higher bandwidth, less affected by electromagnetic interference). The most suitable communication protocols shall be chosen (e.g., TCP/IP, or custom protocols).

Buoy to buoy sensors

The installed microcontroller or data logger should be linked with buoy's installed sensors (meteo-station, GPS module, sondes if any) with specific sensors interfaces.

Power and data Tether

A constant connection between the docking station via the mechanical, power, and data-communication tether should be established. Tethering should be durable and resistant to environmental conditions. The power tether should handle the voltage and current required by the AUV for charging. The maximum power demand based on the AUV's battery capacity and charging rate should be calculated. The required tether length based on the distance between the buoy and the docking station should be determined. Depending on water depth, environmental conditions, and operational goals the underwater tether pathing should be considered. This could either be aligned with the mooring line, which will minimize entanglement risk or separate to allow greater flexibility. Two separate cables could be an option for data and power transfer, respectively.

4.2 Docking station

Mooring

The docking station must be as solidly placed as possible. Preferably positioned on the sea bottom. Ideally it would have to be at a depth less affected by underwater currents.

The docking station needs to be positioned outside of the archaeological area and in a distance from the artefacts to be monitored. Any mooring post necessary to position the docking station must be arranged outside the archaeological area or in points distant from the artefacts. A minimum distance of ~20 meters from the nearest artefact will be planned when identifying the mooring point for the docking station.

4.3 Development of Control center and UX

The purpose of the control center is to monitor sensor data and execute autonomous missions in real time. More specifically, the data collected by the Buoy is periodically (e.g 1sec) sent to the control room in order to supervise the status of each sensor as well as the measurements it receives. Also, the autonomous missions, after initially being loaded in the control room, are sent to the AUV via the Buoy for their execution. In summary, the main functions of the control room are the following:

- Monitor sensor status and data in real time
- Manage autonomous missions

Integration: To achieve communication between the control center and the Buoy, the following steps should be taken:

- define the message bus (Kafka Server, RapidMQ, WebSockets, etc)
- analyze all necessary Buoy sensor data.
- define the message type as well as the message structure.

To send the autonomous missions the following should be defined:

- define the message type as well as the message structure

4.4 Development of LIBS sensor

The fundamental component of the LIBS system is a 532 nm double pulse laser capable of generating pulses with an energy of approximately 40 mJ and a repetition rate of up to 15 Hz. A significant objective is the attainment of a working distance (the distance between the LIBS system and the sample) of 100 – 300 mm. Accordingly, the optical configuration must comprise a one-dimensional laser scanner, enabling the laser beam to be positioned on the sample surface in a flexible manner for the purpose of scanning lines. It is necessary to integrate a beam superposition between the laser scanner and the laser itself, so that the spectrometer beam path can be superimposed on that of the laser. This is essential for the capture of light emitted from the laser-generated plasma in a coaxial configuration with the spectrometer.

The following objectives were defined as part of the development of the LIBS sensor:

- It is imperative that the system be capable of operation at a minimum water depth of 100 meters, with the use of a pressure housing.
- The device is designed to be compact and lightweight, allowing for integration on the AUV.
- Use of a green 532 nm double pulse laser with approx. 40 mJ pulse energy
- Long working distance of up to 300 mm
- Flexible beam deflection for generating line scans with approx. 50-100 mm

Energy

The energy requirement of the LIBS sensor depends entirely on the measurement duration and frequency. As expected, the laser beam source will be the largest consumer of the LIBS system. The highest energy requirement is in the heating phase up to operating temperature. With a voltage supply of 24 - 28 V, a peak current of 19.5 A (according to the laser manufacturer) can be achieved.

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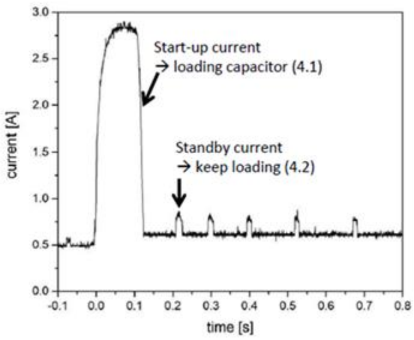
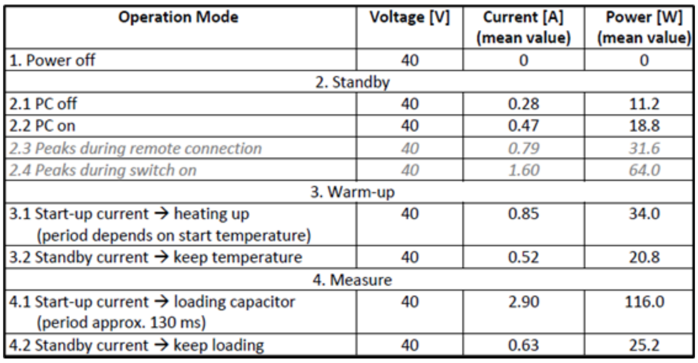
→ A lower power supply and therefore a longer heating time is currently being tested regarding feasibility.

→ Consumption during measurement is currently determined by the laser manufacturer.

This is the expected consumption. In addition, there are other consumers such as the spectrometer, the mini-PC, and other electrical components. An exact statement can only be made after testing the entire setup.

Based on data from an earlier EU research project (ROBUST GA-No. 690416), which also dealt with the development of a LIBS sensor, the measurement curve for different operating modes for the Nerites project can be roughly estimated in advance. Figure 1 shows the actual curve over time and also lists the measurements for the different operation modes.





Operation Mode	Voltage [V]	Current [A] (mean value)	Power [W] (mean value)
1. Power off	40	0	0
2. Standby			
2.1 PC off	40	0.28	11.2
2.2 PC on	40	0.47	18.8
2.3 Peaks during remote connection	*40*	*0.79*	*31.6*
2.4 Peaks during switch on	*40*	*1.60*	*64.0*
3. Warm-up			
3.1 Start-up current → heating up (period depends on start temperature)	40	0.85	34.0
3.2 Standby current → keep temperature	40	0.52	20.8
4. Measure			
4.1 Start-up current → loading capacitor (period approx. 130 ms)	40	2.90	116.0
4.2 Standby current → keep loading	40	0.63	25.2

Figure 1: Example power requirements for LIBS system depending in operation mode (Example: Project ROBUST)

Data Specifications

- **Accuracy**: to be determined later in project
- **Precision**: to be determined later in project
- **Sensibility**: to be determined later in project
- **Resolution**: ~ 0.1 nm
- **Data format:** text file
- **Measurement Units:** Wavelength in nm and intensity in counts
- **Detected substances**: Cu, Pb, Zn, Ni

4.5 Mid-infrared laser-based water analyzer development

Alpes Lasers (AL) focuses on developing a mid-IR quantum cascade laser-based sensor system. For the NERITES project, AL will utilize an External Cavity Laser Kit (ECLK), which includes a Quantum Cascade Laser (QCL) gain chip, a grating-tuned extended optical cavity in Littrow configuration, laser drive electronics, an ALPES TC-3 temperature controller, and graphical user interface software. This ECLK is compatible with the ALPES range of Broad Gain QCLs, which can tune over a range of up to 25% of their central wavelength. Along with the EC-QCL's, AL will provide driving electronics for its devices, as well as to control 3rd party components.

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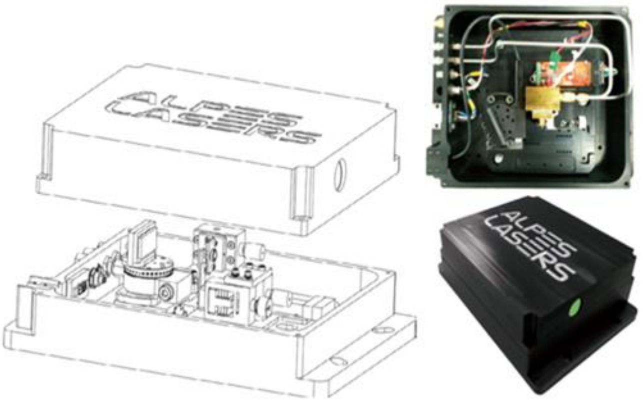

Figure 2: Typical current product: External Cavity Laser Kit (ECLK)

Development of sensors will be defined using epitaxial material and the experimental plan to design the sensing capabilities of the EC-QCL in order to cover the set of desired wavelengths for the detection of targeted materials. The targeted materials will be given in close collaboration with the partners during the project. The fabrication process for the selected wavelengths includes a tailored made IR laser targeting hydrocarbons, Nitrates and Phosphates with an EC-QCL's design which includes laser at spectral range between 1010 and 1345 cm^{-1} and average power around 10 mW at 5% duty cycle, following the requirements of the current deliverable. AL will work in close collaboration with UULM partner in order to provide a complete optical mid-IR sensor that will ensure the minimized power loses, optimize robustness, enable heat dissipation and cooling for the device. Below a set of specifications can be found.

Dimensions

The module is 110mm wide and 120mm high, the depth (beam axis) is 160mm (Additional space is required for the connections). There need to be at least 6 mm of matter at the bottom to fix it and a thermal contact need to be managed there as well or water cooling need to run into the EC base via build in quick connect for OD4 mm tube.

Power supply

The power supply needs to be 24V DC 4 A, barrel jack.

Electrical interface

IN - SMA - Analog input 0-3.3V (16 bits) that can perform signal acquisition synchronously with the emitted wavelength, pulse by pulse.

IN - SMA - Analog input 0-3.3V (12 bits) that can perform signal acquisition synchronously with the emitted wavelength, pulse by pulse.

OUT - SMA - Analog output 0-3.3V (12Bit) where a large portion of the range represent the actual wavelength emitted with high bandwidth.

IN or OUT - SMA - Trigger for laser burst / Mode of operation dependent

IN or OUT - SMA - Trigger for laser pulse / Mode of operation dependent

OUT - SMA - Pulse synchronization signal with adjustable pulse length / Mode of operation dependent

OUT - SMA - Pulse synchronization signal with actual pulse length

IN - SMA - Interlock / need to be bridged.

DB26 connector - Various IN/OUT and status signal dependent of operation mode.

USB C - Connection to the single board computer that act as EC controller and provide data logging, graphical interface and script execution.

EC Controler SBC

Raspberry pi, Linux based OS.

Design

- The QCL gain chip and grating-tuned extended optical cavity in Littrow configuration. Compatibility with ALPES Broad Gain QCLs tuning over up to 25% of their central wavelength, giving degree of freedom of 200 cm^{-1} from the central wavelength.

Energy

- The QCLs will be emitting in a few tens of mW optical power (50 watts maximum energy consumption), if operating continuously.

Temperature

- Actively regulated by a heatsink assembly with a thermoelectric element and water cooling for improved heat dissipation. Working temperature for the EC-QCL's is 20° ⍰ 5° and temperature control should be always monitored to ensure the efficient working capability of the QCL sensor. The thermal dissipation is less than 8W total.

Integration and Miniaturization

- Custom-designed for AUV-mounted sensors for water pollutant measurement. Emphasis on miniaturized and ruggedized configuration, suitable for the constraints of AUV platforms. Low power consumption, close to 8W in order to cope with AUV integration.

Wavelength and Optical Specifications

- Wavelength coverage and tuning range to detect specific target analytes. Optical power requirements: minimum optical power and maximum electrical consumption.

Fabrication and Testing

- Selection of appropriate epitaxial materials and definition of experimental plans. Fabrication process considerations including integrated micro-heater geometrical dimensions, laser cavity length, and width. Prototypes tested under environmental conditions (temperature and vibration) using TestEquity model TE-115A temperature chamber and TIRA model TV 55240/LS-340 vibration test system. Measurement of output power, spectrum, beam divergence, and beam pointing during temperature and vibration tests.

Technological and Economic Optimization

- Selection of the optimum solution from a techno-economic perspective. Development of tailored-designed IR laser sources targeting hydrocarbons and other compounds of interest.

Pressure and Environmental Specifications

- Replaceable ATR pressure cell designed to withstand up to 2 MPa pressure (corresponds to 20 bar pressure expected at a depth of 200 meters). Dual-crystal ATR system with a robust IR-transparent waveguide sensing interface. ZnSe or diamond optics to couple IR radiation from the QCL into the waveguide-based sensing interface. The crystal mounts must be able to withstand the corrosive saltwater conditions. In order to be able to evaluate the IR data more precisely, additional auxiliary sensors (oxygen-, pH-, temperature sensors) may also be integrated into the IR sensor system.

Control and Integration

- Integration with ALPES' TC-3 temperature controller and graphical user interface software. Compatibility with driving electronics and control for both ALPES and third-party components.

Data Specifications

- **Accuracy**: to be determined later in project
- **Precision**: to be determined later in project
- **Sensibility**: to be determined later in project
- **Resolution**: Concentration Depended variations. Typically, 0.005 cm^{-1}
- **Data format**: txt, csv, ascii
- **Measurement Units**: wavenumbers (cm^{-1})
- **Detected substances**: TOC - Total Organic Compound, VOCs-Volatile Organic Compound, Phosphate Nitrate

4.6 AutoMP module

During NERITES, CERTH will develop an Autonomous Energy-Efficient Mission Planning module, responsible for surveying known (charted) UCH areas. The tool will use hierarchical deep learning schemes for optimized dynamic (mission execution time) tasks planning. To train such modules, appropriate simulation models are needed, considering the detailed 3D terrain map of the UCH areas' topographic representation. During NERITES such terrain map will become available by utilizing the AUV that is coupled with conventional bathymetric sonars and cameras. This map will serve as the foundational layer upon which mission planning will be based.

The operational hierarchy of the tool considers a pipeline of two stages: macro- and micro-scopic mission planning. The first step involves defining the intermediate 3D waypoints that the Autonomous Underwater Vehicle (AUV) is required to navigate through, in order to take the UCH required samples. The aforementioned macroscopic checkpoints will be generated at the mission initialization stage, according to the requirements of each mission that will be predefined by the involved end-users.

The second step considers the generation of greater granularity intermediate checkpoints (between two macroscopic ones) taking into consideration potential environmental dynamics of higher granularity. Such intermediate microscopic checkpoints will be generated on the fly when the AUV reaches the starting macroscopic checkpoint of the specified subsequence of the mission. The mission plan always starts and ends at the coordinates of the docking station, ensuring that the AUV begins each mission fully charged and returns for recharging at the end. This approach guarantees that the AUV is ready and fully powered for each subsequent mission.

In order to enhance energy efficiency, the AutoMP module will consider energy consumption, time and expected difficulty/risk in its objective function, both for the macro and the micro scopic stages. This will ensure that the AUV can complete its mission with minimal energy expenditure. In order to achieve that, the AI algorithms will analyze various mission parameters, including the distance between waypoints, the AUV's speed, impact of external disturbances, and the terrain's topography, to determine the most energy-efficient route.

In addition to optimizing the mission for energy efficiency, the AutoMP module incorporates real-time data from the AUV’s hardware and software-based sensors. This data includes information about the underwater environment, such as water currents, obstacles, localization and the presence of marine life, which could impact the AUV's navigation and energy consumption. Continuously monitoring these environmental factors, the AutoMP module enables the AUV to adjust its path in order to avoid obstacles and take advantage of favorable conditions, thus enhancing the energy efficiency both during the macro and the microscopic stages.

The AutoMP module further supports the update of its mission in real-time, ensuring adaptability and responsiveness to the unexpected and dynamic underwater conditions. For example, if the AUV encounters unexpected challenges, such as changes in water conditions or previously undetected obstacles, the AutoMP module can replan the route in real-time to ensure mission success without compromising its energy efficiency.

The AutoMP module’s technical requirements and steps are:

• **Initial Mapping**:	Detailed map of UCH areas acquired using AUV as foundational layer for mission planning.
• **Waypoint Definition**:	Intermediate 3D waypoints defined by end users and integrating partners based on sampling requirements.
• **Mission Planning**:	AutoMP designs mission plan including initial, intermediate, and final waypoints starting and ending at docking station.
• **Energy Efficiency Optimization**:	Utilizes Reinforcement Learning algorithms to optimize the AUV’s path while taking under consideration energy consumption.
• **Task Description**:	Tasks (e.g., sampling) at waypoints are generated to effectively manage energy consumption while considering complex operations.
• **Real-time Data Integration**:	Considers real-time data from AUV sensors for potential path adjustments based on environmental factors, enhancing safety and energy efficiency.
• **Multi-objective Optimization**:	RL algorithms balance energy efficiency with mission objectives such as mission duration and sample collection.
• **Real-time Adaptability**:	Module updates mission plan in real-time to address unexpected challenges without compromising energy efficiency.

4.7 Optical sensing for photogrammetry

Selection of the optimum solution from a techno perspective, the Nerites project’s AUV platform would be based on cameras (one on the front for evaluation of artefacts’ degradation and another looking downward for safety navigation and landing) with high photo resolution (e.g., 27MP) and video capabilities (e.g., up to 5.3K at 60fps, HDR). Moreover, advanced stabilization (i.e., HyperSmooth 6.0) will improve underwater measurements. In addition, the optical sensors will be able to support various fields of view (ranging up to 177°). More details about photogrammetry will be specified during the development and implementation of the project.

Data Specifications

- **Spatial resolution (3D reconstruction)**: to be specified in the implementation
- **Mapping Accuracy (GSD)**: of 0.5mm/pixel for Percentage % of biological colonization; 0.1 mm/pixel for Level of biodegradation (1-5 classes).
- **Data format**: to be specified during development
- **registration misalignment error**: < 0.5 % for 4D analysis.

4.8 Protocols for UCH Surveying

The degradation of cultural heritage materials represents a significant threat to their preservation. In underwater environments, historical and archaeological materials on the seabed exhibit various forms of deterioration and conservation conditions. These decay processes are primarily influenced by the differing and dynamic exposure conditions and are also related to the intrinsic properties of the constitutive materials. The relationship between cultural heritage and the surrounding environment is crucial in studying the degradation processes of underwater resources. Experts emphasize the necessity of assessing environmental parameters and their interactions with the mineralogical and petrographic properties of materials to plan effective diagnostic and conservation strategies for protecting underwater cultural heritage (UCH).

Degradation can be defined as a set of processes that alter the physical, morphological, and aesthetic structure of an artefact or archaeological site.

Given the unique characteristics of each UCH site and the specific degradation phenomena that occur, an Operational Protocol has been developed within Nerites project. This protocol, comprehensively described in D2.3, outlines a methodology for designing specific monitoring strategies tailored to the unique conditions of each UCH site. This structured approach enables tailored monitoring and conservation efforts, ensuring that the distinct conditions and challenges of each UCH site are effectively addressed. It encompasses several key elements, including the selection of sensor combinations, correlated analysis methodologies, integration of auxiliary sensors, determination of measurement intervals, establishment of sample sizes and measurement quantities, data formatting considerations, among others.

The protocol mandates a meticulous selection of sensors, ensuring their compatibility and suitability for capturing data parameters relevant to the specific degradation phenomena occurring at a given UCH site. This careful selection process is crucial for obtaining accurate and comprehensive data, which is essential for understanding and mitigating degradation processes.

The following table provides a detailed list of the sensors and technologies to be used in the Nerites protocol. A more detail description will follow in the Deliverable D2.3. The table outlines the requirements for their appropriate use in the Nerites monitoring program, including the specific parameters to be detected, the substances or effects of degradation to be measured, and the necessary accuracy and sensitivity:

Table 1: List of sensors and technologies

Measured Material/Area	Degradation or features detected	Parameters detected	Substances /effects of degradation	Technology used	Measurements Units and sampling
Stone and ceramic *(mosaic tesserae, mortars, marble slabs, bricks, amphoras)*	Chemical/environmental degradation	Presence of heavy metals	Cu, Pb, Zn, Ni	LIBS	Wavelength [nm] intensity [counts] 1 or 2 samples chosen at the beginning of the survey
Sediment	Chemical/ environmental degradation	Presence of heavy metals	Cu, Pb, Zn, Ni	LIBS	Wavelength [nm] intensity [counts] 10 samples chosen at the beginning of the survey
Archaeological metals	Metal alloy	Presence of elements in the alloy	Cu, Pb, Zn, Ni (ex.)	LIBS	Wavelength [nm] intensity [counts] Sample chosen in selected area
Sediment	Chemical/ environmental degradation	Presence and % of Total Organic Compound	TOC – Total Organic Compound	QCL	mg/kg 10 samples chosen at the beginning of the survey
Sediment	Physical and chemical properties of the boundary conditions	pH at the sea-sediment interface	Acidity or alkalinity	pH Sensor probe over samples	pH
Water column	Chemical/ environmental degradation	Concentration of chemical compounds	VOCs-Volatile Organic Compound	QCL	µg/kg
Stone and ceramic (mosaic tesserae, mortars, marble slabs, bricks, amphoras)	Biological degradation	Percentage of biological colonization (covering)	Perforated areas (e.g. holes, bioerosion traces) Encrusted/covered areas (patinas, algal felts)	Photogrammetry, 3D models and automatic image analysis	% on a reference area (size of the sample area)
Stone and ceramic (fragment of mosaic floor, walls, masonries, amphoras)	Degradation forms (besides biological)	Identification of degradation forms (besides biological)	Fractures, collapses, detachments, removals, losses	4D Analyses	Critically reference areas identified within the UCH site
Water Column	Physical and chemical properties of the boundary conditions	Water column profiles	Acidity or alkalinity	CTD Vertical casts	pH
Water Column	Physical and chemical properties of the boundary conditions	Water column profiles	Temperature	CTD Vertical casts	°C

Water Column	Physical and chemical properties of the boundary conditions	Water column profiles	Dissolved O_2	CTD Vertical casts	Ppm
Water Column	Chemical/ environmental degradation	Concentration of chemical compounds	Phosphate, Nitrate	QCL	µg/kg
Water Column	Chemical/ environmental degradation	Concentration of chemical compounds	Dissolved CO_2	CTD Vertical casts	µg/kg

The Nerites protocol outlines a comprehensive approach to analyzing and monitoring the degradation of UCH sites. It includes various types of analyses, such as chemical, biological, and structural assessments, that are specifically aligned with different degradation phenomena. By integrating these diverse analyses, the protocol ensures a holistic understanding of the factors contributing to the deterioration of UCH sites. In addition to primary sensors, the protocol also requires the deployment of auxiliary sensors. These auxiliary sensors augment data collection and enhance the accuracy and reliability of measurements by capturing supplementary environmental parameters that influence degradation. Measurement intervals are another crucial aspect of the protocol. The frequency and timing of measurements as to be carefully defined to capture temporal variations in degradation phenomena effectively. These intervals are determined based on the dynamic nature of the degradation processes and the specific conditions of each site. The protocol also provides guidelines for determining the appropriate sample size and the number of measurements required. This ensures statistically robust data collection, taking into account the heterogeneity of UCH site characteristics. By considering these factors, the protocol ensures that the data collected is representative and reliable. Finally, standardized formats for data collection, storage, and analysis have to be specified. These standardized formats facilitate interoperability, reproducibility, and data sharing among researchers and stakeholders. By adhering to these standards, the protocol promotes consistency and collaboration in the study and conservation of underwater cultural heritage.

5 References

1. Nerites Deliverable 2.1 ‘Pilot surveys and use case scenarios definition’
2. Nerites Deliverable 2.3 ‘Framework for the systematic degradation assessment of UCH’