THE RESEARCH PROJECT BLU-ARCHEOSYS: INNOVATIVE TECHNOLOGIES AND ADVANCED SYSTEMS IN SUPPORT OF UNDERWATER ARCHAEOLOGY

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1. Introduction

More than a year has passed since the industrial research project BLU-ARCHEOSYS (Innovative technologies and advanced systems in support of Underwater Archaeology) was closed (only formally). It has involved several years of collaboration between companies, research centers and universities and has produced a great quantity and quality of scientific results whose applications range from the sector of archeology of water and submerged Cultural Heritage to industrial sectors such as the oil and gas industry (surveys, support to construction of offshore structures, oil and gas pipelines), the telecommunications industry (support for the installation and maintenance of cable ducts); military applications; security and civil protection applications; underwater mining operations; environmental monitoring and investigations; geological monitoring; monitoring of diving infrastructures; fishing industry; education; entertainment.

The objectives of the project were designed to lead to the implementation and testing technologies vertically integrated in each of the stages of the value chain of the submerged Cultural Heritage and therefore related to: reconnaissance, prospecting, geophysical surveys, discovery, recovery, detection, excavation, documentation, protection, transportation, environmental protection and enhancement, restoration, maintenance, preservation, end-user enjoyment and 'musealization' [1].

2. Enabling technologies for the study of underwater heritage

Within the BLU-ARCHEOSYS project, two research groups have developed new technologies that can be used directly in the underwater world. We are talking about the first 3D scanning device based on radar technologies, and a multi-component Remotely Operated Vehicle (ROV) system, capable of carrying a complex set of measurement technologies useful in analyzing different aspects of the seabed [2,3].

2.1. The U-ITR developed by ENEA

In the field of underwater environments, the research center ENEA Frascati (Rome), has developed a 3D vision system called Underwater Imaging Topological Radar (U-ITR) (Fig-

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ure 1). The system is able to perform 3D scans in an underwater environment. The results obtained by ENEA tell us that it is possible to see in 3D, underwater, using radar technology.

Intense research activity has been carried out, covering theoretical study and a series of experiments carried out in two test tanks, respectively 1.5 m and 25m in length, relative to the propagation in water with different degrees of turbidity of a Continuous-Wave (CW) laser beam amplitude modulated (AM-Amplitude Modulation) of wavelength λ=405nm (blue/violet zone in visible spectrum) with the aim of obtaining information that is useful and essential in the field of 3D imaging for applications in underwater environments [4].

Tests with the prototype U-ITR in the test pool, involved the laser scanning of some metal targets immersed in relatively clean water, such as perforated discs with holes in the order of 1mm, circular flanges, stepladder with fixed and well-established spaces between rungs (in the order of 1 cm). The range and breadth of data acquired with the U-ITR during scans, made it possible to reconstruct 3D models of high quality, high resolution (of the order of 1mm to 4-5m distance) and which were extremely accurate, of the submerged targets under investigation, thus demonstrating a great opportunity to use the U-ITR as a diagnostic tool for the conservation state of artifacts of interest in underwater environments, such as archaeological sites, and as a tool for inspecting and monitoring the status of pipelines and anchor chains of offshore oil or gas rigs.

The use of underwater optical radar may naturally be generalized to 3D viewing of structures in underwater environments, which do not necessarily belong to the field of archaeological assets, such as oil rigs and the like. As a result, interest in security and surveillance has become increasingly important in recent years.

Figure 1. The U-ITR system

2.2. A multi-component ROV developed by Ageotec

Ageotec srl, a leading Italian company in the production of systems for underwater exploration, developed an innovative Remotely Operated Vehicle in its laboratories during research for the BLU-ARCHEOSYS project. The system is not only able to accommodate the module for 3D vision realized in ENEA Frascati, but also a number of sensor systems whereby it is possible to measure different variables in the underwater world and carry out targeted sampling.

The main objective to be achieved, was the realization of the ROV demonstrator, whose characteristics are summarized in the following tables.

General Characteristics	**Demonstrator (Only vehicle without accessories)**
Dimension	length 1000 mm width 800 mm height 800 mm
Weight in air	160 kg
Maximum operating depth	1000 m
Propelling and corresponding forces maximum	2 vertical motors, 100 kg 4 horizontal motors, 100 kg forward and 50 kg lateral
Load capacity	40 kg

ROV features

Features of the instrumentation	**Demonstrator (Only vehicle without accessories)**
Cameras / lights	4 video channel with fiber optic transmission plus 1 video channel on bipolar twisted cable.
Instrumentation that can be installed	Interfacing: CP Probe, Octans, 2022 R2Sonic and similar Panoramic Sonar, Bathymetric System, altimeter, current meter, Pipe Tracker, multiparameter probes. Data transmission with fiber optic multiplexer.
Navigation	Gyro Flux-gate, angular accelerometer, pressure sensor (depth)
Control	Video overlay on monitor with video recording. Export via serial sensor data. Software system diagnostics (external PC connected to the console surface) Demultiplexer in optical fiber.
Supply	400 VAC three-phase, 10 kW (free flight), 30 kW (option TMS)

Features of the module on board the ROV

Figures 2 and 3 illustrate the demonstrator vehicle ROV in one of its typical configurations, which, in addition to the navigation components, also includes the acoustic vision multibeam scanning system (installed cantilever in the front) and attitude and navigation sensors (installed in the rear). The architecture was kept highly modular to allow operational characteristics to be adapted as a function of the operating scenario in the intended application.

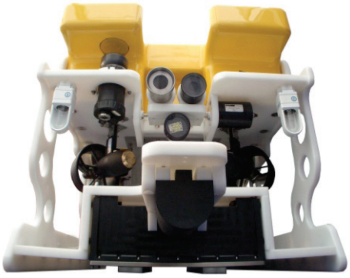


Figure 2. Configuration of the vehicle type ROV demonstrator fitted with sonar systems and structure and navigation

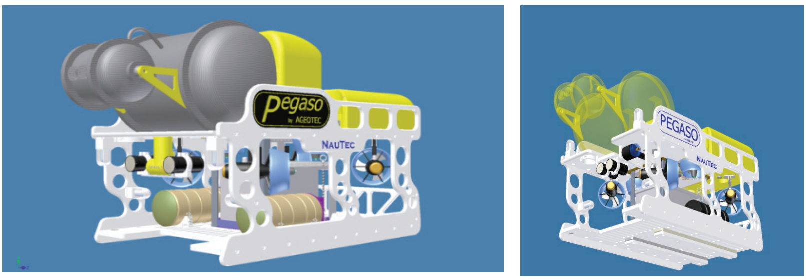


Figure 3. concept of ROV with Pegasus configuration that can accommodate the UTR

3. Visual Information System and virtual simulation

Virtual reality is an important key enabling technology within the BLU-ARCHEOSYS project. Two main fields of research are addressed by the research team:

1) Simulation of the underwater scenario
2) Finite element method for the recovery simulation.

3.1. Simulation of the underwater scenario

While Ageotec researchers were developing the ROV system, the CETMA consortium laboratories in Brindisi, were dealing with all the problems of post-processing scientific data acquired by the system in the underwater environment. The use of the 3D reconstruction of the seabed, of multibeam type (or multibeam echosounder), developed for the ROV, thanks to collaboration between the University of Bologna and Ageotec, enabled the research team, composed of computer technicians from CETMA, to create a processing system capable of:

- reviewing mission data (review of the ROV mission);
- simulating a mission on the reconstructed seabed starting from the cloud acquired by the multibeam.

The first step was implemented within the Virtual Reality Centre built by the consortium in the past and put at the disposal of the project. In order to develop applications in 3D immersive real-time mode, a processing of more partial data (strips), and the reconstruction of triangulated surfaces was carried out (Figure 4). The last step before obtaining the final dataset (data from the mission) was to apply texture mapping algorithms, so that during the viewing, there is a realistic feeling of being on the seabed.

A further task was then to use the dataset of the reconstructed seabed (Figure 5) in order to produce a real ROV mission simulator. In order to achieve this, for the simulation part of the degrees of freedom, a robotic platform was used in which real-time applications were developed to incorporate both the motion dynamics of the ROV and the management of the immersive scenarios. The platform can be used both to review activities during missions and to provide material for training and briefings. For the modeling of the dynamics of a generic underwater vehicle, a model designed and built by the "Naval Post Graduate School," the NPS AUV II, was used (Figure 6).

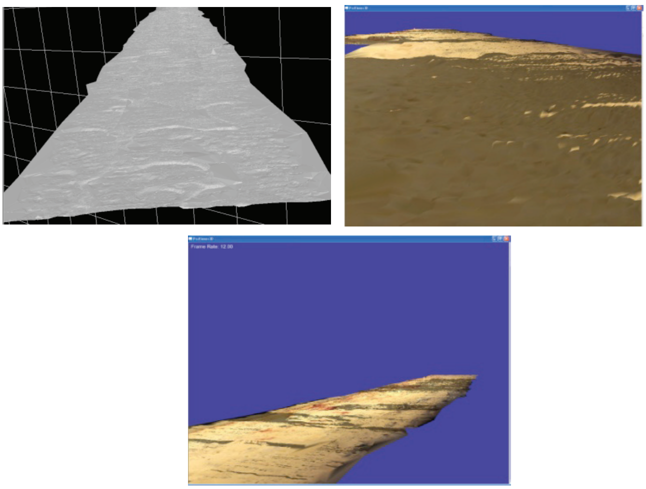
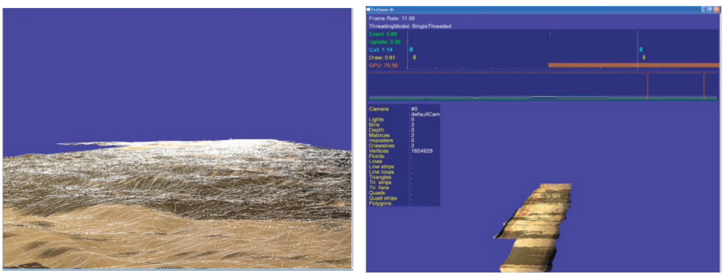


Figure 4. Display the point cloud as a result of the triangulation and mapping of color with the navigation module Real Time



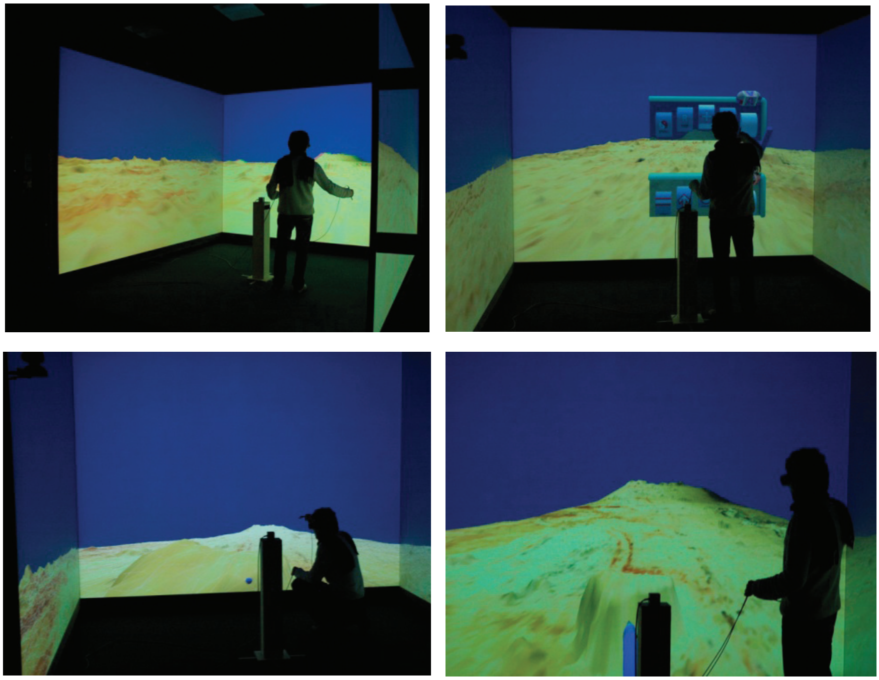


Figure 5. Use of the seabed within the CAVE of CVRC

Figure 6. simulator interfaces

3.2. Virtualization and finite element numerical analysis method

Technologies of virtualization and finite element numerical analysis were also used in simulating the recovery process, thanks to collaboration between the simulation experts of the CETMA division of Materials and Structures Engineering and the group from Chemistry of the Environment and Cultural Heritage at the University of Urbino. The method was developed using artifacts from the wreck of a sailing ship (dated by the University of Salento to the Renaissance period). The finite element analysis provides a methodological approach which can be outlined in three distinct phases:

- Pre-processing phase: chemical/physical/mechanical characterization of materials
- Processing phase: numerical calculation
- Post-processing phase: visualization of results.

In brief, a logical flow of activities of ROV data post-processing was identified that, starting from the 3D model of the wreck and the properties of the materials that compose it, enables the analysis for a possible recovery project.

On the basis of the wood samples provided and the experimental tests that were carried out (Figure 7), it was possible to define the mechanical characteristics of the material of the specimen (Figure 8). The results of the mechanical characterization were used to implement the numerical models of behavior of the materials in the calculation code Ls-Dyna (Figure 9).

The behavioral model of the material made it possible to analyze, by means of specific numerical simulations, what the possible hypotheses were for the recovery project. In fact, referring to a 3D model of the wreck, it was possible to evaluate whether the recovery solution was appropriate or not (Figure 10).

Two possible recovery solutions were analyzed (Figure 11-12) together with the critical areas of strength (final mapping of the stresses on the component). The finite element model which was developed, also allowed other recovery solutions to be considered and to include any geometric and structural changes to the suggested system (Figure 13).

Figure 7. Subsequent splitting of the specimen

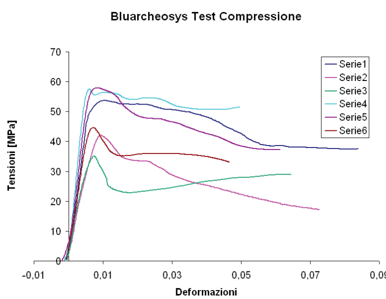


Figure 8. Tension strain curves of compression tests

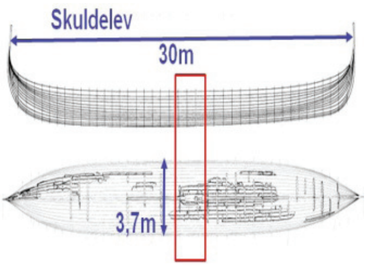


Figure 9. Model and size of Skuldelev 2

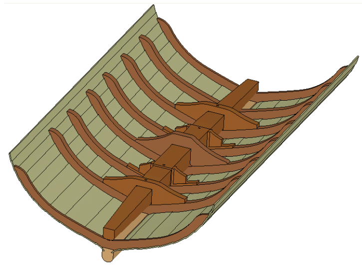


Figure 10. Finite element model used for simulation of recovery

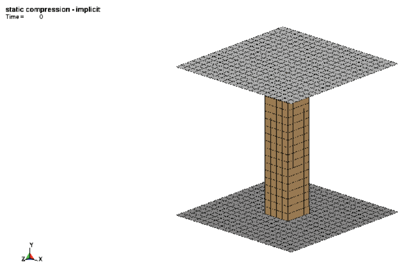


Figure 11. Finite element model of the compression test

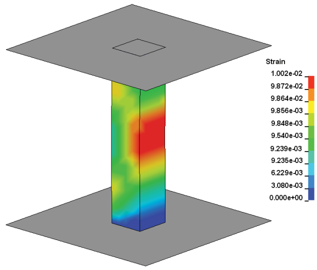


Figure 12. Finite element model of the compression test

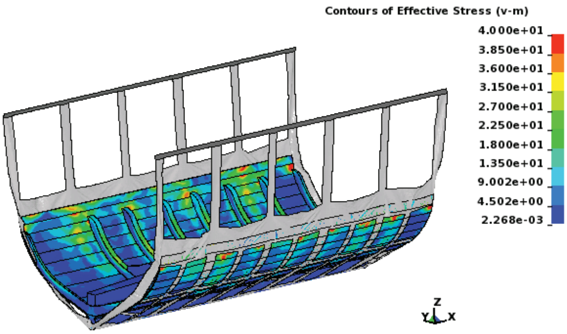


Figure 13. Post processing data

4. An innovative technology for the morphological characterization of underwater finds

One of the most interesting activities in the BLU-ARCHEOSYS project, concerned the realization of a complex system that can simultaneously perform different measurements of morphological nature for any artifact, the system integrates:

a) A CT scan with a source of 250 MeV
b) A laser line surface scanning system
c) A colorimeter
d) A micro profilometer.

The machine is unique (Figure 14); its construction involved researchers in the CETMA consortium (for the mechatronics module), researchers of the CNR-INO (for the optical measurement modules), and researchers at the University of Bologna (for the tomography module). Below are some pictures of the constructive schemes and implementation phases of the constituent parts and the system as a whole. The machine was then tested on a specimen provided by the Superintendence of the Sea of Palermo (amphora).

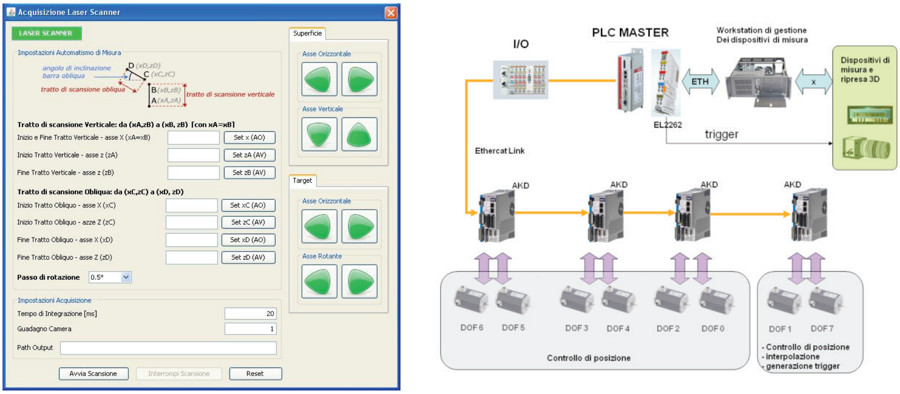
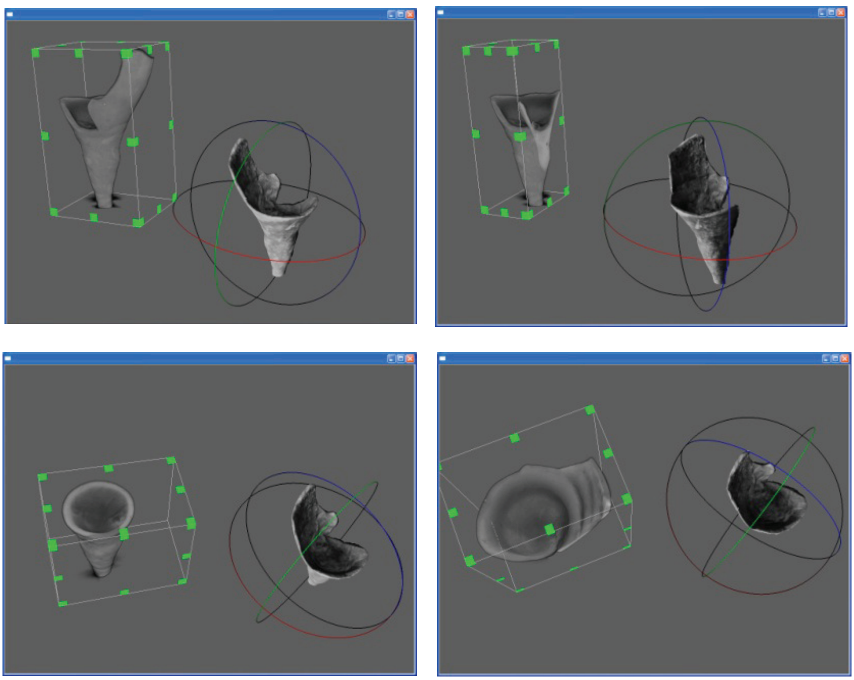


Figure 14. The machine and its control system

The FRAMEWORK software for managing the hardware devices integrated into the machine of morphological characterization for measuring, enables interfacing, using special software libraries written in C++, to the real hardware devices such as: laser scanner, colorimeter and micro-profilometer connected to the computer via USB and surface roughness meter (“*rugosimetro*”) connected to the computer via Ethernet [5].

Below are the results of a multi-measurment (TAC + Laser Scanning) carried out in the laboratory on a fragment of amphora provided by the General Directorate of the Superintendence of the Sea of Palermo (Figure 15).



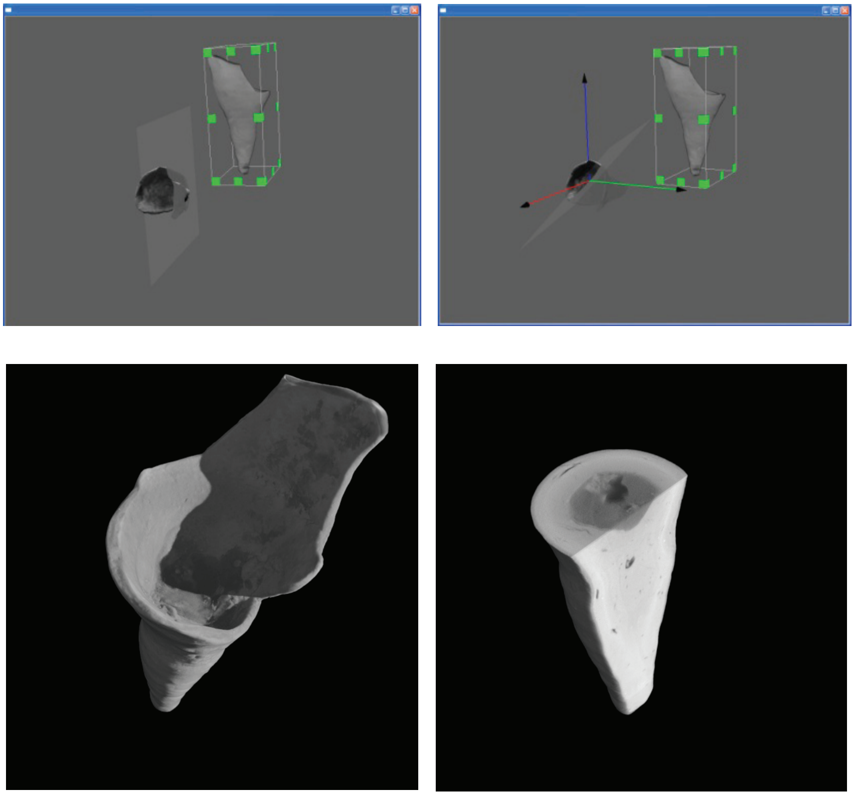


Figure15. fusion of different dataset in 3D

5. Complex technology for the analysis of underwater finds

Technologies for the analysis of samples and archaeological finds are an interesting line of research within the BLU-ARCHEOSYS project. These were conducted by the University of Salento and coordinated by Professor Lucio Calcagnile, Professor of Applied Physics, Department of Innovation Engineering.

The most important research was carried out in the CEDAD laboratories - Center for Dating and Diagnostics Department of Innovation Engineering of the University of Salento. The Department made it possible to design and implement a multi-isotope beam line, associated with the particle accelerator 3MV TANDETRON (Figure 16), able to carry out isotopic analysis and dating, up to tens of millions of years.

Before implementation of the new line, dating was carried out only by measuring radiocarbon with a dating range of up to about 50,000 years. Thanks to the BLU-ARCHEOSYS project it has been possible to extend the range of dating of materials, using the ^{10}Be rather than ^{14}C, up to about 15 million years. The line was designed in collaboration with the Group of Physics of Ionic Beams of the Swiss Federal Institute of Technology in Zurich (ETH) and is capable of directly measuring radioactive particles that are extremely rare in nature, including ^{10}Be, ^{26}Al, ^{129}I, ^{238}U with a technique known as Accelerator Mass Spectrometry (AMS). Implementation of the new dating system required the engineering of two large magnets (one weighing 7 tons) and an electrostatic analyzer for selection in mass, energy and charge of the various radioactive isotopes. All the electronic acquisition and particle counting system was developed by the Group of Applied Physics, Department of Innovation Engineering. The new beam line connected to the accelerator will allow CEDAD to conduct research in various fields, from archeology to geology, from hydrology to Earth and Environmental Sciences [6, 7, 8, 9].

Figure 16. The hall of the accelerator TANDETRON CEDAD (left) and the new multi-line isotope (right)

A second activity involved the design and implementation of a system for dating waters for research on hydrology and climatology. The system (Figure17) consists of a vessel containing water from which CO_2 has to be extracted and connected by means of various valves in cryogenic traps for the freezing and entrapment of carbon dioxide and the evacuation of gases from the sample. Transfer of the gases is accelerated by the injection of a carrier gas, usually helium. The production of CO_2 occurs by chemical reaction with phosphoric acid, with subsequent entrapment and catalytic reduction in graphite for measurement with the accelerator of the carbon isotopes.

Figure 17. The dating system of water

A third activity focused on the engineering of a mechanical system for the collection of samples which are then extracted from marine sediments containing radioactive isotopes to be measured by AMS. The results of these activities have been presented at numerous national and international conferences in the field.

6. New analytical methods of investigation

But the BLU-ARCHEOSYS project has not only played an important part in developing new technologies, it has also identified innovative analytical methodologies. On this issue, interesting work has been conducted by the University of Bologna and in particular that regarding studies carried out on Punic amphorae in the "Baglio Anselmi" Museum of Marsala (Trapani). As part of the BLU-ARCHEOSYS research project, the methodology related to the knowledge of Punic amphorae samples from the "Baglio Anselmi" Museum of Marsala (Trapani) has been developed.

The underwater world is full of wrecks, artifacts and relics testifying to eras, populations and socio-economic and cultural levels, as well as products, and manufacturing techniques where very diverse materials and functions have been used, and which in fact, need to be studied from a historical archaeological-bibliographic and technical-material-analytic point of view. The study of the appropriately chosen amphorae, was initially directed at aspects of a technological and commercial nature, and therefore, connected to the routes of ships with different destinations and, however, attributable to commercial circuits in certain production areas (Figure 18).

The 33 specimens were cataloged using technical data sheets prepared with the relevant historical and archaeological, typological and production data. The Punic amphorae displayed in the museum are heterogeneous from the point of view of typology and chronology, and can be placed in a time period ranging from the seventh century. B.C. to the seventh century. A.D.

The province of Trapani and the area of Palermo is where the largest number of Punic amphorae have been found compared to other areas of Sicily.

Their distribution is concentrated, in fact, in the Punic centers of great importance in Western Sicily: Mozia, Marsala, Trapani and Pantelleria.

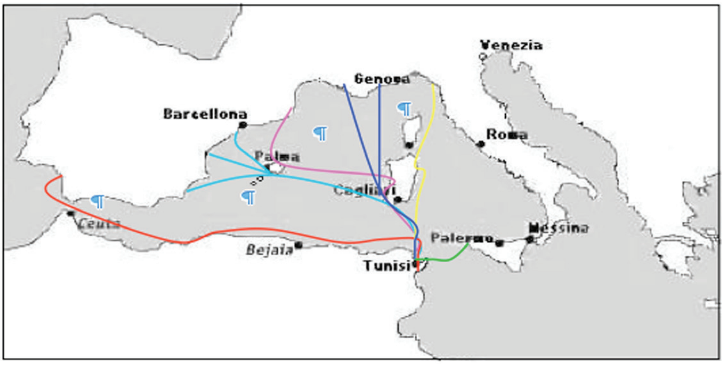


Figure 18. Probable trade routes of some types of amphora

To perform the characterization of the materials constituting the artifacts to be studied, with the assessment of their conservation status, about 15 of the amphorae (selected on the basis of their integrity, excluding some specimens, which being unique, may testify in time to their uniqueness), the following analyses were performed:

- X-ray diffraction (XRD) (Figure 19)
- spectroscopy with Fourier transform infrared (FT-IR)
- thermogravimetric analysis (TGA)
- thermo analysis (DTA)

Figure 19. Diffractometer X-ray

The study of Punic amphorae from the “Baglio Anselmi” Museum in Marsala (Figure 20) has helped to catalogue a number of the specimens on display and has led to significant results regarding the distribution of amphora typologies in Sicily.

The diagnostics for the characterization of materials constituting the artifacts under examination and assessment of their conservation status is not only fundamental for any subsequent restoration but also to refute or confirm hypotheses regarding the main production sites, obtained on the basis of bibliographic sources, and to trace back the material composition of these artifacts to their sites of origin.

Figure 20. Amphorae

7. The BLU-ARCHEOSYS training project

The BLU-ARCHEOSYS research project was also linked to a specific training project, with the goal of creating specialized professionals in the application of innovative technologies in human studies and operations in underwater environments.

The educational part of the training project of BLU-ARCHEOSYS envisaged a single educational objective implemented directly by the CETMA Consortium headquarters in Brindisi with the aim to train “Specialist Researchers in the Application of Methodologies and Technologies to Support Underwater Archaeology”.

The training program was developed from the idea of forming new professional profiles for integrating into research activities in the field of underwater archeology through the acquisition of specific skills on methodologies of study and analysis, recovery techniques and underwater diving skills, the use of innovative technologies, including those directly resulting from the same research activities (closely related to the research programme).

Beneficiaries of the training project were 9 graduates, found to be suitable in the selection phase and recipients of a scholarship. In detail, the training, related to increasing in-depth specialized technical knowledge, has covered issues of purely scientific themes, and those more closely related to historical-humanistic disciplines. Below is a breakdown of the topics covered in the different sub-modules:

Submodule A1 - Elements of Computer Basics
Submodule A2 - Fundamentals of Physics
Submodule A3 - Fundamentals of chemical, biological and ecological sciences
SubMod. A4 - Fundamentals of Materials Science
SubMod. A5 - Coastal Geology and Geomorphology.
SubMod. A6 – Historical-archeological and philological culture
SubMod. A7 - Robotic systems
SubMod. A8 – Prospecting methods and systems
SubMod. A9 - Non-destructive diagnostic techniques
SubMod. A10 - Dating Techniques
SubMod. A11 - Electron Microscopy techniques
SubMod. A12 - Underwater Archaeology and naval archeology
SubMod. A13 - Enhancement of underwater heritage
SubMod. A14 - Knowledge of the system artifact-environment
SubMod. A15 - Underwater archaeological surveying and prospecting methodologies
SubMod. A16 - Underwater diving qualification

The above modules also included training in learning to assess and organize industrial research projects, managing R&D in industry, acquiring knowledge of legislative and regulatory issues in the field of cultural heritage.

Educational activities generally provided a methodology for structured training in:

- lessons in the classroom with teachers and external personnel (university professors and researchers, PhD researchers and experienced professionals and qualified ESA instructors - for the section regarding the scuba diving qualification);
- practical-applied classroom activities, individual and / or group;
- laboratory activities;
- practical lessons for diving operations carried out by qualified ESA instructors, these activities were completed with the acquisition by the participants of 8 ESA Patents (Open Water Diver, Advanced Diver, First Aid, Prevention & Rescue Diver, Nitrox Diver, Orienteering Diver, Deep Diver, Archeo Diver);
- operation and experimentation alongside researchers and experts working in the BLU-ARCHEOSYS Research Project host structures and partners, with a period of on the job training in a company and individual work under supervision and coordination in the same structures to develop independence through specific activities of study, research, drafting of documents, data processing and laboratory experimentation (period of professional specialization).

In detail, work placements were held at the following locations:

- CEDAD - CEnter dating and Diagnostics-Dep. Ing Innovation - University of Salento-c / o Citadel Research Brindisi;
- INOA, National Applied Optics-Smart Arnesano (Lecce);
- NAUTILUS COOPERATIVE - Vibo Valentia;
- Diagnostic Laboratory for Cultural Heritage of the Department of History and Methods for the Conservation of Cultural Heritage, Alma Mater Studiorum University of Bologna, located in Ravenna and Diagnostic Laboratory at the CTA

(Centre for Advanced Technology) based in the Inter-university Consortium for Trapani;
- CETMA Consortium-Department of Computer Engineering - c/o Citadel Research Brindisi.

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At the end of this extraordinary journey, I would like to thank a few people who were immensely important, not only in achieving the objectives of the project, but also because of the human relationships that provided a fertile ground for many a challenge. A special thank you goes to Professor Salvatore Lorusso, for his wisdom and tenacity. We met in January of 2004 and it was in that meeting he told me for the first time about this idea for a project, by producing a short but fundamental paper. Thanks also to Professor Lucio Calcagnile, whose contribution was crucial for the most ambitious goals of the project. Thanks also to the representatives of all the technical and scientific partners of the project: Dr. Luca Pezzati (CNR INO), Dr. Pietro Basciano (Ageotec), Professor Giuseppe Spoto, Dr. Dipietro Antonino (Dipietro Group), Giorgio Fornetti (Enea), Professor M. Letizia Amadori (University of Urbino). I also thank Professors Paolo Mazzoldi and Mario Lombardo for coordinating the training project in such a masterly way.

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Biographical notes

Lucio Colizzi is an Information Technology engineer. After many years of experience in ICT, robotics, Virtual Reality and data processing and modeling, in 2001 he became the ICT department Director of CETMA. Until now he has co-ordinated important national research programs and in the last ten years has also been coordinator on several projects in the field of development of technologies for cultural heritage. He has obtained many post-graduate qualifications: BPR, Concurrent Engineering and Quality Function Deployment, STEP -ISO 10303, Simple ++, eM-Plant, eM-Planner, Informix Dynamic Server Administration and Performance Tuning, Design For Manufacturing & Assembly, Object Oriented design with UML, Microsoft certifications: C#; ADO.NET; ASP.NET; XML Web services.NET; PROJECT MANAGEMENT (Bocconi University). As a result of his many interests, he has taught “Project Management and Group Dynamics” as Adjunct Professor at the universities of Bologna and Lecce.