ARCHAEOLOGICAL ROBOT SYSTEMS FOR THE WORLD'S SEAS

ARchaeological RObot systems for the World's Seas – Project n. 308724

Final Project Report (with answers)

Due date: Aug 31st, 2015	Delivery date: March 25th , 2016
Project start date: September 1st, 2012	Responsible Partner: UNIFI
Involved Partner(s): ALL	Version: 2.0

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1. Project Objectives

The ARROWS project started on September 1st, 2012 and its whole duration is three years; thus on August 31st, 2015 the end of the project was reached. The project proposes to adapt and develop low cost autonomous underwater vehicle technologies to significantly reduce the cost of archaeological operations, covering the full extent of archaeological campaign. The goal of the second (and last) period of the project (since mid-term – February 28th, 2014 – to the end of the project) was mainly the testing of the prototypes designed and developed during the first period and their integration in the overall system. This activity had the main purpose of preparing the ARROWS technology to be ready and capable to demonstrate its potentialities in real scenarios. The methodology followed in the second period was the same one that demonstrated to be successful in the first period. According to the guidelines and the feedback provided by the archaeological partners of the project (DBCIS and EMM) and by the Archaeological Advisory Group (AAG), the technical partners developed Hardware and Software solutions to achieve the goals of the project, being compliant with the archaeological requirements.

More in details the activities mainly carried out in the second period are:

1. Vehicles and tools testing – the different vehicles involved in the ARROWS project (the developed ones Typhoon AUVs, MARTA, U-CAT, A_sized AUV and the commercial ones Iver3 and Remus) was tested and improved according to the tests feedback in order to be ready to demonstrate the expected capabilities during the final demonstrations. The different payloads (optical and acoustic ones) were also tested as stand-alone devices at the beginning

and integrated with the vehicles before the final demonstrations. The developed cleaning tool was also tested in laboratory during a first phase and in the sea in the following.

2. Development of the system for fruition – a system for the fruition of the available data and the ones that will be acquired in the future was prepared. An interactive mixed reality environment for virtual exploration of underwater sites through the navigation of realistic graphical models was also developed and tested.

3. Final demonstration preparation and completion – a considerable effort was dedicated to the organization of the two final demonstrations of the project. The demonstrations were carried out in the Summer of 2015; a first one was carried out in the Aegadian Archipelago (Sicily, Italy) whereas the second one in Estonia (Rummu quarry and Tallinn bay).

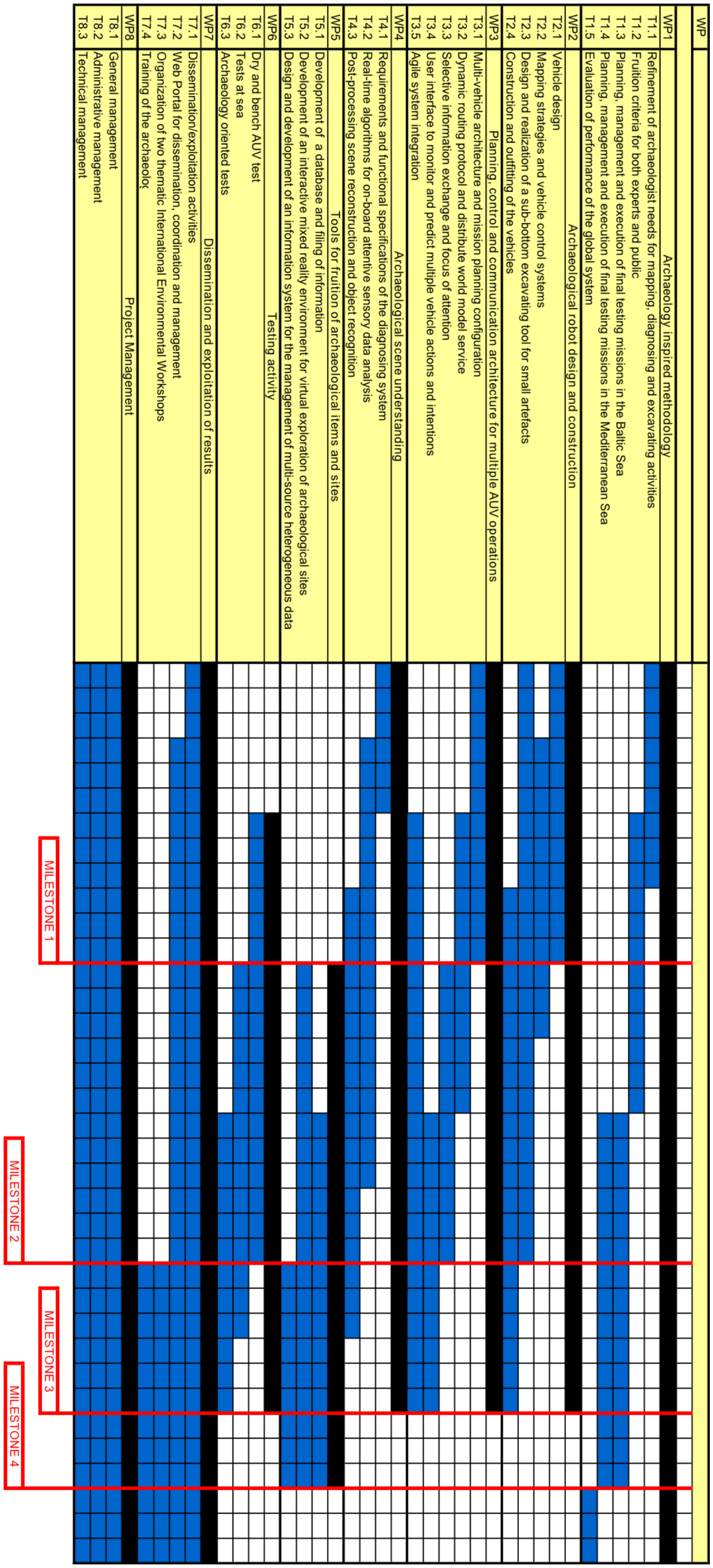
4. Dissemination activity – the dissemination was also one of the main activities to which the consortium dedicated a remarkable effort in the second period of the project. The two thematic workshops organized during the first period of the project were successfully carried out during the 2014 as planned. In addition, exploiting the results obtained within the project, a scientific dissemination activity was carried out with publication of different works both in conference proceedings and on peer-reviewed journals.

Each partner provided its contribution towards the two successful demonstrations performed in the Summer 2015 in two different places as the Mediterranean Sea (Aegadian Archipelago) and the Baltic sea (Tallinn Bay and Rummu Quarry). The activities described in the Description of Work and the goals of the project have been achieved despite some deviations from its original version agreed with the Commission and the Project Officer during the project period according to different consideration explained also in this document.

2. Project achievements: Work Packages completed

To summarize, all the deadlines described in the ARROWS DoW have been satisfied; in particular, the Milestones of Month 12 (Design), of Month 24 (Tests on single vehicles), of Month 30 (Test on teams) and of Month 33 (Fruition methodologies) have been fully carried out.

ARROWS was composed of eight Work Packages (WP), one of them dedicated to the project management. According to the Gantt chart of the project (reported in the following):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ARROWS

- **WP1 – Archaeology Inspired Methodology:**
  - Starting Month: 1
  - Ending Month: 36
  - Lead Beneficiary: DBCIS
  - Number of tasks: 5
- **WP2 – Vehicle Design:**
  - Starting Month: 1
  - Ending Month: 30
  - Lead Beneficiary: UNIFI
  - Number of tasks: 4
- **WP3 – Planning, Control and Communication Architecture for multiple Autonomous Unmanned Vehicle Operations:**
  - Starting Month: 1
  - Ending Month: 30
  - Lead Beneficiary: HWU
  - Number of tasks: 5

- **WP4 – Archaeological Scene Understanding:**
    - Starting Month: 1
    - Ending Month: 30
    - Lead Beneficiary: UNIFI
    - Number of tasks: 3
- **WP5 – Tools for Fruition of Archaeological Items and Sites:**
    - Starting Month: 13
    - Ending Month: 33
    - Lead Beneficiary: CNR-ISTI
    - Number of tasks: 3
- **WP6 – Testing Activity:**
    - Starting Month: 7
    - Ending Month: 30
    - Lead Beneficiary: EL
    - Number of tasks: 3
- **WP7 – Dissemination and Exploitation of Results:**
    - Starting Month: 1
    - Ending Month: 36

    - Lead Beneficiary: EL
    - Number of tasks: 4
- **WP8 – Project Management:**
    - Starting Month: 1
    - Ending Month: 36
    - Lead Beneficiary: UNIFI
    - Number of tasks: 3

In the following the project achievements are described, WP by WP.

2.1.1. WP1 - Archaeology inspired methodology

SUMMARY, TASKS AND OBJECTIVES

The aim of the first Work Package of the project mainly included two activities:

- Formal definition of the requirements for the system and of the fruition criteria according to the archaeologists' necessities and experience with the objective of defining the guidelines for the work of the whole consortium in all the Work Packages; because of the goals of this first activity, for its nature, it concluded with the first half of the project. The achieved results were compliant with the expected ones as described in details in the following;
- Organization, planning and management of the two final demonstrations in the Baltic Sea and in the Mediterranean Sea with validation and analysis of the results; the tasks related to these activities were instead performed in

the second half of the project.

Here are the results achieved during the project:

- **T1.1 - Refinement of archaeologist needs for mapping, diagnosing and excavating activities (Months 1-9):** the activity carried out in the framework of task T1.1 involved the two archaeological partners of the project (DBCIS and EMM) and the ARROWS AAG. The followed methodology includes meetings among the involved archaeologists who, according to their experience and to the European legislation on the subject, defined the requirements for the vehicles both for missions in open sea and inside the wrecks. Moreover, an important effort was dedicated to deepen the topic of excavation of submerged artifacts; the results of this discussion was a deviation from the ARROWS DoW, in fact the archaeologists community, according to the 2001 UNESCO Convention for the Protection of Underwater Cultural Heritage, considers the excavation an activity to be avoided. Instead, support of robotics for cleaning activities of well-known underwater artifacts would be appreciated by archaeologists who periodically have to spend a lot of time and money for maintenance (mainly modern metal artifacts cleaning). Finally, preliminary indications for the final demonstrations have been agreed and provided to the consortium describing the environment to be expected, the recommended periods and the past experiences had on the same or similar sites. Deliverable D1.1 - *Report about archaeologist needs for mapping, diagnosing, excavating activity* describes the results reached in the framework of the task T1.1 and the process followed to achieve them.

- **T1.2 - Report about fruition criteria archaeology oriented (Months 7-18):** the activity carried out in the framework of task T1.2 involved CNR-ISTI in addition to the archaeological partners of the project. CNR-ISTI was the responsible partner of WP5 about Tools for Fruition of Archaeological Items and Sites and worked closely together with the archaeologists in this task in order to achieve a complete state of the art about the common fruition tools and their degree of development. The methodology used for task T1.2 included also a questionnaire to be used to perform a survey of known practices and regulations submitted to a series of institutions, including Sicily, Tuscany, Estonia, UK, Croatia, Germany, Spain, UNESCO and various Non EU countries (e.g. North Africa, Tunisia, Libya, Egypt). As result of the activity of the task, a complete survey of the common practice for all the phases of data management (collection, record, fruition, exploitation, protection encryption and licensing) in the underwater archaeology field has been carried out. Deliverable D1.2 - *Report about fruition criteria archaeology oriented* describes the results reached in the framework of the task T1.2 and the process followed to achieve them.

- **T1.3 - Planning, management and execution of final testing missions in the Baltic Sea (Months 19-33):** the activities carried out within this task focused on each phase of the process that led to the final test mission in the Baltic Sea. Tallinn bay has been identified as the test site. The task leader, Estonian Maritime Museum, planned this mission choosing the specific place and the period in accordance with its experience in underwater archaeology in the Baltic Sea area. The testing phases were carried out in accordance with the regulations of the local competent authorities.

  The testing of autonomous underwater robots, in particular MARTA by UNIFI, the U-CAT by TUT and the commercial AUVs REMUS and IVER3 by HWU, was performed in Tallinn Bay and in the Rummu quarry (Tallinn, Estonia) from the 16th to the 24th of July 2015. All these tests were organised by the Estonian Maritime Museum and the Centre for Biorobotics of the Tallinn University of Technology. Deliverable D1.3 - *Mission log of the Baltic Sea testing mission* describes the results reached in the framework of the task T1.3, i.e. during the ARROWS final demo in Estonia, and the process followed to achieve them.

- **T1.4 - Planning, management and execution of final testing missions in the Mediterranean Sea (Months 19-33):** the activities carried out within this task focused on each phase of the process that led to the final test mission in the Mediterranean Sea. The Aegadian archipelago (Sicily, Italy) has been identified as the test site. The task leader Soprintendenza del Mare Regione Sicilia, DBCIS, planned this mission choosing the specific place and the period in accordance with its experience in underwater archaeology in the Mediterranean Sea around Sicily, Italy. The testing phases were carried out in accordance with the regulations of the local competent authorities.

  The testing of autonomous underwater robots, in particular Typhoon AUVs and MARTA by UNIFI, the A_Size AUV by EL, the U-CAT by TUT and the commercial AUV IVER3 by HWU, was performed in front of Levanzo Island, Aegadian Archipelago (Sicily, Italy) from the 25th May to the 6th of June 2015. Moreover, the Cleaning Tool was tested as a stand-alone device in the port of Trapani. All these tests were organised by the Soprintendenza del Mare Regione Sicilia. Deliverable D1.4 - *Mission log of the Mediterranean Sea testing mission* describes the results reached in the framework of the task T1.4, i.e. during the ARROWS final demo in Sicily and the process followed to achieve them.

T1.5 - Evaluation of performance of the global system (Months 34-36): the amount of data, collected during the final and the back to the site testing missions, has been processed and has been the basis for drafting the report on the evaluation of both the Mediterranean and Baltic Sea tests. DBCIS and EMM were respectively responsible for the reports on Mediterranean Sea mission and on Baltic Sea mission. Deliverables D1.3 - *Mission log of the Baltic Sea testing mission*, D1.4 - *Mission log of the Mediterranean Sea testing mission* and D1.5 - *Evaluation report about the* *testing and back-to-the-site missions*, contain the analysis of the results achieved by the global system.

SIGNIFICANT RESULTS

The outcome of the task T1.1 is reported in the deliverable D1.1 – *Report about archaeologist needs for mapping, diagnosing, excavating activity* that formally defines the achieved results:

- Requirements for the vehicles in terms of positioning, size, cost, observation capacity, modular system;
- Requirements for AUV propulsion system;
- Definition of main issues for exploration inside modern wrecks;
- Definition of the excavating as a "cleaning tool";
- Definition of environmental conditions for both the Mediterranean Sea and the Baltic Sea and description of the Underwater Cultural Heritage (UCH) for the demonstration sites.

The outcome of the task T1.2 is reported in the deliverable D1.2 – *Report about fruition criteria archaeology oriented* that formally defines the achieved results:

- Results of the survey of known practices and regulations;
- Results of the survey of existing record standards for the management

of UCH;

- Classification of data typologies;
- Classification of data collection methodologies;
- Description of the proposal of a record structure for ARROWS Project;
- Classification of stakeholders and users involved in the management of UCH;
- Definition of the policies for the fruition of the data collected by ARROWS Platform;
- Definition of data exploitation, protection, encryption and licensing methods;
- Classification of available software components and tools for data management and fruition.

The outcome of the task T1.3 is reported in the deliverable D1.3 – *Mission log of the Baltic Sea testing mission* that formally defines the achieved results:

- Choice of testing locations, and prior studies;
- Results of the testing activities in the Rummu quarry;
- Results of the testing activities in the Tallinn Bay.

The outcome of the task T1.4 is reported in the deliverable D1.4 – *Mission log of* *the Mediterranean Sea testing mission* that formally defines the achieved results:

- Sites description;
- Test planning and mission execution;
- Results of the testing activities in the Aegadian Archipelago.

The outcome of the task T1.5 is reported in the deliverable D1.5 – *Evaluation report about the testing and back-to-the-site missions* that formally defines the final comments related to the ARROWS final demos:

- Technical evaluation;
- Archaeological evaluations;
- Costs evaluation.

ISSUES, DEVIATIONS FROM ANNEX I AND USE OF RESOURCES

The consortium in collaboration with the Archaeology Advisory Group of the project decided to avoid the construction of a tool for excavating purposes as described in the ARROWS DoW aiming, instead, at the design, the construction and the integration on MARTA AUV of a tool to be used for cleaning campaigns. The excavation, according to the 2001 UNESCO Convention for the Protection of Underwater Cultural Heritage, is not a practice to be used for UCH that, instead, has to be left in the environment where it has been found. In addition, the excavating activity would probably damage the stratigraphy of the area causing a loss of very important data. The underwater archaeologists would instead benefit a lot from the availability of a "cleaning tool" integrated with robot. This would accelerate the timing and reduce the costs of maintenance activity for well-known underwater artifacts that periodically need a cleaning activity against marine flora that may grow up on them or deposits of mud in order to preserve their integrity.

2.1.2. WP2 - Vehicle design

SUMMARY, TASKS AND OBJECTIVES

Work Package 2 covers all the phases of the vehicles' construction, from their design to their completion. In particular, four tasks, were dedicated to the four main activities:

- **T2.1 - Vehicle design (Months 1-12):** the activity carried out in the framework of task T2.1 has been faced within the VDG (Vehicle Design Group) established during the Kick-off meeting of the project, including representatives from all the partners involved in the design activities. The result of the carried out activity is the detailed design of the project vehicles, achieved according to the requirements stated by the archaeologists in the framework of WP1. An iterative process based on feedbacks coming from meetings among the involved partners brought to the final version of the three new vehicles, A_Sized AUV, MARTA and U-CAT, with responsible partners respectively EL, UNIFI and TUT. Deliverable D2.1 – *Biomimetic Robot Design* describes the details of the design of U-CAT explaining the reasons that stand at the basis of the main taken choices. Deliverable D2.2 – *AUV Design* is divided into two sections, one dedicated to MARTA and one dedicated to A_Sized AUV, and describes the details of the design of the vehicles explaining the reasons that stand at the basis of the main taken choices.

- **T2.2 - Mapping strategies and vehicle control systems (Months 4-15):** the aims of this second task are the design and the implementation of the low-level software for each vehicle. The low-level software includes control system for motion control, driver for all the on-board devices, simple acquisition of data from payload and management of critical (alert or emergency) conditions. EL, UNIFI and TUT developed this software, ROS (Robot Operating System) based, respectively for A_Sized AUV, MARTA and U-CAT in agreement with the decisions taken within the SIG (Software and Integration Group), established during the Kick-off meeting of the project, including representatives from partners involved in the software design activities. The process has been of iterative kind with each step forward based on the results of an important simulation activity and on the discussion within the SIG. During this task concluded at month 15 of the project with, as result, the low-level software for the three new vehicles ready and successfully tested in simulation. Deliverable D2.3 – *Biomimetic robot control system* includes a description of the U-CAT software architecture with implementation details for the main components. In the same way, D2.4 – *AUV control system* includes two sections, one dedicated to MARTA software and one to the A_Sized AUV one.

- **T2.3 - Design and realization of a sub-bottom excavating tool for small artifacts (Months 1-24):** According to the decision taken in the framework of WP1 about the construction of a "cleaning tool" instead of an excavating one, the activity of the task T2.3 started with the beginning of the project and ended at month 24. The activity carried out in the framework of T2.3 is in close collaboration with the other tasks of WP2; an important integration effort has been spent in order to build a cleaning tool that affects the least possible the dynamic behavior of the vehicles. The requirements imposed by the consortium concerned the dynamic impact on the vehicle, the power adsorption and the dimensions of the tool. A first prototype of the tool has been built within the half of the project time with the support of NESNE that shared with the consortium its experience about cleaning tools previously developed for underwater nets. Deliverable D2.5 – *Design and realization of a sub-bottom excavating tool for small artifacts – 1st release* describes the activity carried out for task T2.3 and the achieved results highlighting the performance of the first release evaluated through a laboratory testing activity. Then the consortium, in particular NESNE with the support of AMT, worked on the optimization of the prototype reaching its final version. Deliverable D2.6 – *Design and realization of a sub-bottom excavating tool for small artifacts – final release* describes the final version of the cleaning tool developed and built during ARROWS project. The device was successfully tested stand-alone (some results are given in the Deliverable D6.2 – *Sea test report*), it was also mounted on an AUV but because of the weather conditions during the final demos (in particular strong currents) the consortium decided not to test it in open waters for safety reasons.

- **T2.4 - Construction and outfitting of the vehicles (Months 10-30):** The aim of the task T2.4 was the construction of the vehicles. Three construction teams were in charge for the three new vehicles built within ARROWS. EL for the A_Sized AUV, MARTA by the MDM Lab of the University of Florence in Pistoia (IT) and U-CAT built in Tallin at TUT. The construction activity followed the guidelines specified in the deliverables that summarize the design process. The results of this task are the final versions of the prototypes of the vehicles. The prototypes of A_Sized AUV, MARTA and U-CAT are described in the related deliverables D2.7 – *Biomimetic robot prototype #1* , D2.8 – *AUV prototype #1* and D2.10 – *AUV team prototype*. The task T2.4 ended at month 30 of the project. These three AUVs are fully working prototypes and they have been tested during the ARROWS final demos (in the Mediterranean Sea and in the Baltic Sea).

SIGNIFICANT RESULTS

The outcome of the task T2.1 is reported in the deliverables D2.1 – *Biomimetic* *robot design* and D2.2 – *AUV design* that formally defines, for each vehicle, the achieved results:

- Formal AUV specification from archaeologists requirements;
- General architecture;
- Electrical hardware design;
- Propulsion system;
- Structural design;
- Vehicle modules design.

The outcome of the task T2.2 is reported in the deliverables D2.3 – *Biomimetic robot control system* and D2.4 – *AUV control system* that formally defines, for each vehicle, the achieved results:

- Definition of the overall software architecture;
- Definition of the main ROS packages;
- Definition of the payload management;
- Definition of the communication management;
- Success of the simulation tests;
- Successful integration with high-level control system modules available.

The outcome of the task T2.3 is reported in the deliverables D2.5 – *Design and realization of a sub-bottom excavating tool for small artifacts – 1st release* and D2.6 – *Design and realization of a sub-bottom excavating tool for small artifacts – final* *release* that formally define the achieved results:

- Formalization of specifications for the cleaning tool;
- Two different versions of the cleaning tool built and tested;
- Cleaning tool prototype characterization through testing activity in laboratory and at sea (stand-alone device).

The outcome of the task T2.4 is reported in the deliverables D2.7 – *Biomimetic robot prototype #1* , D2.8 – *AUV prototype #1* and D2.10 – *AUV team prototype* that, for each vehicle, formally define the achieved results:

- Vehicle specifications;
- Vehicle architectures;
- Vehicle characteristics;
- Electromechanical description.

ISSUES, DEVIATIONS FROM ANNEX I AND USE OF RESOURCES

The three deviations from the original ARROWS DoW (see dedicated section 3.5) affect this Work Package and its tasks. In particular, the work of tasks T2.1, T2.2, T2.3 and T2.4 was dedicated to the successful design and construction of two different kind of AUV instead of two copies of the same vehicle. As regards the "main AUVs", at the beginning of the project, the first idea about the external diameter of the cylindrical body was to assume a diameter not bigger than 120 mm (the so-called A_Sized); after several considerations (summarized in the Deliverable "D2.2 – AUV Design"), and according to the vehicle specifications (e.g. autonomy and requested devices) and to the partner suggestions, the final diameter of MARTA AUV is about 180 mm (7 inches).

MARTA is the AUV (Deliverable "D2.2 – AUV Design") compliant with the archaeologists' requirements, formalized in the AAG report and officially delivered to the commission as Deliverable "D1.1 - Report about archaeologist needs for mapping, diagnosing, excavating activity". AAG requirements lead to a certain kind of vehicle with high performance, such as hovering capability, accurate acoustic localization, precise dead reckoning by means of DVL and FOG in case of missing acoustic fix, etc..

Moreover, the partner EL has identified an interesting market segment for an A_Sized vehicle, so in the framework of ARROWS they designed and built a 120 mm diameter vehicle (A_Sized AUV). The A_Sized AUV, although with downgraded performances with respect to the MARTA mainstream design, is a very small, easily deployable and cheaper AUV. The construction of these AUVs was successfully completed, sharing components selection and design solutions as much as possible. In the consortium opinion, this is a strength and an enrichment of the project, rather than a menace.

Also the decision of the construction of a cleaning tool instead of an excavating one affects WP2, task T2.3 in particular that is dedicated to this topic.

Finally, the consortium decided to build a single well working U-CAT prototype (biomimetic robot) instead of a team: this affects the work of task T2.4. As far as the biomimetic robot is concerned, a solution with a novel four-flipper turtle-like robot has been developed. The biomimetic robot U-CAT is capable of moving in all the 6 degrees of freedom. Such a system has several advantages compared to traditional propeller-driven systems and a fish-robot type system developed previously in TUT. However, developing a new biomimetic actuation system has added multiple high risk activities to the design and manufacturing process. To get a desired performance of the actuation subsystem, far more design, prototyping, and testing iterations than initially foreseen were needed. This is not a complete surprise since the rather unconventional novel design of the four-flipper propulsion has all the features of a "high risk -- high gain" research activity. The effort spent by TUT in order to have it properly working has been more than foreseen.

So the consortium has decided not to build a second biomimetic robot and concentrate the effort on having the U-CAT prototype #1 in good shape to be used in team with the other ARROWS vehicles.

In any case, neither the timing of the project and its value did not suffer from these deviations.

2.1.3. WP3 - Planning, Control and Communication Architecture For Multiple Autonomous Unmanned Vehicle Operations

SUMMARY, TASKS AND OBJECTIVES

Work Package 3 mainly deals with the definition and the implementation of the high-level control system on the project vehicles. The objective of WP3 is the development of algorithms and software, compatible with the involved AUVs and BRs, capable of autonomously manage their behavior during an archaeological campaign so that each vehicle is able to undertake autonomously decisions in order to satisfy the overall goal of the mission. The activity carried out for WP3 mainly took place in close collaboration with the Software and Integration Group (shortly: SIG); in fact, an important effort has been dedicated to smoothly integrate the high-level control system with the low-level one on the different vehicles. The work under WP3 is subdivided into five tasks, four of them with starting date in the first half of the project period and one, task T3.4 about "User Interface to Monitor and Predict Multiple Vehicle Actions and Intentions" whose starting date coincides with the half of the project and that lasts for one full year. Two out of the five Tasks that compose the Work Package are basic tasks in the framework of which preliminary theoretical and first implementation and validation work had to pose the foundations for the final result; these two tasks, indeed, concluded within the first period of the project. In the following, the description of the activity carried out within all the tasks of the WP3 is summarized along with the specific results achieved in each one of them:

- **T3.1 (Months 1-12) - Multi-Vehicle Architecture and Mission Planning Configuration:** The goal of task T3.1 has been the adaptation of software and algorithms, previously developed by HWU, capable of allocating specific goals to the different platforms (AUVs for ARROWS project) cooperating for the success of the mission. The effort, spent for this task, particularly focused on the integration and modification of previously existent software, ROS based, to be suitable and optimized for new ARROWS vehicles – object of WP2 – and with on-board payload – object of WP4 – different for each AUV. The result has been successfully achieved thanks to a close collaboration among partners in the framework of the Software and Integration Group. The results of the work of T3.1 are described in the deliverable D3.1 – *Multi-vehicle architecture* that include a formal definition of the architecture and ontology-based mission planning systems. The activity related to this task successfully concluded in the first year of the project providing the expected results useful for the following of the project (i.e. formal definition of the elements of the architecture for cooperation of multiple autonomous vehicles).
- **T3.2 (Months 7-18) - Dynamic Routing Protocol and Distributed World Model Service:** Task T3.2 has been of fundamental importance for the definition of communication protocol among the cooperating AUVs through the use of acoustic modems that is the only communication means available in the underwater environment. Available acoustic communication technology, currently, has significant limits regarding transmission band, distance, packet loss and sensitivity to environmental conditions; thus, a dynamic routing protocol able of optimizing data transfer is a necessary condition for a

cooperating team of underwater vehicles. The knowledge of a distributed World Model allows each vehicle to take decisions about the tasks to be performed. Also in this case, the expected results have been achieved within the first period of the project: Dynamic Routing Protocol and Distributed World Model Service were formally defined and, after a further period of six months testing, the World Model was described in the deliverable D3.2 – *World Model Service* with deadline at the end of the second year of the project.

- **T3.3 (Months 13-24) - Selective Information Exchange and Focus of Attention:** The work that was performed in the framework of task T3.3 regards a part of software that, implemented on each AUV, decides which information is necessary to transmit in order to optimize the reduced band width resources offered by the acoustic communication channel and allowing a smooth and sufficiently frequent data exchange among all the acoustic nodes. An "on a need to know basis" strategy is chosen as solution for this topic. The methodology followed within this task were based on an iterative process starting from results of simulations for a first optimization of the algorithms and continuing with the feedback from the experimental activity carried out in laboratory and in a realistic environment during dedicated on field test campaigns organized during the second period of ARROWS. Results of T3.3 activity, according to the specific contribution, are partly reported in Deliverable D3.2 – *World Model Service* and Deliverable D3.4 – *Overall System Performance and Documentation*.
- **T3.4 (Months 19-30) - User Interface to Monitor and Predict Multiple Vehicle Actions and Intentions:** The activity of this fourth task completely developed within the second period of ARROWS leading to the achievement of user interface for mission monitoring

and prediction. The importance of this kind of tool for the user during a mission is justified by the common external conditions that AUVs have to deal with during sea operations. Indeed, the underwater domain presents an environment which not only has the potential to be extremely hazardous, but is also actively hostile to communication, both between deployed vehicles and to users on shore. Previously, before the ARROWS project, HWU has developed the Back to The Future Engine (BTTF), an advanced mission monitoring interface that uses prediction to maintain the operator's situation awareness when acoustic communication is unavailable or intermittent. By knowing the available planning logic on the vehicle, and with partial knowledge of the world, the BTTF predicts vehicles' likely actions, until communications are restored and all can be resynchronized. In Task T3.3 the goal was the development of the interface for the multi-vehicle case, providing the operator with the ability to slide forwards and backwards in time, visualizing hindcast, nowcast and forecast of vehicles' locations, behavior and plans from current world knowledge. The details that led to the successful achievement of the expected result are described in the Deliverable D3.3 - *Predictive User Interface (BTTF)* where the main interface features and functionalities are provided along with the adopted method for the extension to the multiple vehicles operations.

- **T3.5 (Months 7-30) - Agile System Integration, Testing and Evaluation:** Task T3.5 lasted almost during all the Work Package 3 with the aim of ensuring all the necessary hardware and software to be ready for the final demonstrations. The most important intermediate result achieved within the first period of the project for this task was the successful integration of high-level control with the low-level one that was developed by different teams from different partners. This important goal was achieved thanks to a tight collaboration between all the project partners and in particular within the two working groups (Vehicle Design Group – VDG and Software and Integration Group - SIG). Deliverable D3.4 – *Overall System Performance and Documentation: Report about the evaluation of the performance of the whole system* describes in details the performance of the system developed during the whole project and provides the necessary documentation to describe and clarify the functioning of the main components. D3.4 includes also the intermediate integration results obtained during the field testing campaign held in occasion of the Breaking the Surface 2014 Workshop. These results provided a valuable feedback for the final phases of the project where, during the scheduled final demonstrations, the developed system worked as an integrated entity.

SIGNIFICANT RESULTS

To summarize, significant results achieved in the framework of task T3.1 are the following ones (first project period):

- Definition of the collaborative mission goals;
- Definition of the Multi-vehicle software architecture;
- Formal definition of the Mission Planner layer;
- Formal definition of the Mission Executive;
- Preliminary definition of the World Model Service;
- Preliminary definition of the Communication solutions.

Results achieved in task T3.2 (first project period):

- Formal definition of the communication protocol;
- Formal definition of the World Model Service.

Results achieved in task T3.3:

- Preliminary version of the algorithms for selection of information to be transmitted (first project period);
- Final version of the algorithms for selection of information to be transmitted;
- Final tested version of the Exchange Manager Node for AUVs.

Results achieved in task T3.4:

- Preliminary version of the user interface for mission monitoring and prediction;
- Final tested version of the user interface for mission monitoring and prediction.

Results achieved in task T3.5:

- Successful high-level control system integration with low-level control; system on the project vehicles (first project period);
- Planning of the testing activity for integration evaluation (first project period);
- Integration bench tests performed according to the plan (first project period);
- Integration sea tests performed according to the plan;
- Tests on first version of the architecture for multiple autonomous unmanned vehicle operations;
- Final version of the architecture for multiple autonomous unmanned vehicle operations improved exploiting the feedback from the first tests.

ISSUES, DEVIATIONS FROM ANNEX I AND USE OF RESOURCES

As concerns WP3, no issues or deviations occurred neither during the first period and the second period of the project.

2.1.4. WP4 - Archaeological scene understanding

SUMMARY, TASKS AND OBJECTIVES

In WP4, activities that deal with the analysis of the information captured by inspection and search AUVs and U-CAT biomimetic robot are carried out. More specifically three main topics are addressed:

- Definition of the payload hardware to be mounted on the vehicles to acquire and process optical and acoustic data of the underwater environment. Given the strong connection of this activity with those related to the vehicle design (described in deliverables D2.1 e D2.2), it has been concluded within the first months of the project.
- Design and implementation of algorithms for data analysis directly on board of the vehicles. These algorithms are aimed at providing cues to the High Level Control — through the World Model — so to allow the AUVs to dynamically adapt the planned mission (see WP3).
- Design and implementation of more sophisticated algorithms for data post processing. The output of this activity, that in part refines results obtained with the on-board software, are used as input for the fruition software (see WP5).

To summarize, task T4.1 - Requirements and functional specifications of the diagnosing system, concluded at month 6, encompasses the first activity, while task T4.2 - Real-time algorithms for on-board attentive sensory data analysis and task T4.3 - Post-processing scene reconstruction and object recognition are related respectively to the second and third activities that, at the moment of the Mid-term deadline, started but not concluded. The research and testing activities performed in the second ARROWS period led to the definition of the necessary algorithms for real-time data analysis and for data post-processing. Here in the following the work carried out within each task of WP4 is described and the deliverables, where the details of the achieved results are reported, are indicated.

- **T4.1 (Months 1-6) - Requirements and functional specifications of the diagnosing system**: the carried out activity involved UNIFI, as task leader, plus CNR-ISTI, HWU, TUT, EL, NESNE, DBCIS and EMM. Discussions and updates on this topic have been carried out during the first Skype conferences of the Software Integration Group (SIG). UNIFI, CNR-ISTI, HWU and TUT worked on the definition of the hardware, considering the archaeological groups observations (DBCIS, EMM and AAG), and helped by the industrial partners EL and NESNE. In particular, UNIFI selected the optical hardware of MARTA that includes RGB cameras, illuminators and laser, plus the onboard computer that used to run the on-line algorithms. CNR-ISTI and HWU worked together to review and to choose the acoustic devices to be used on the search and the inspection vehicles, whereas TUT defined the payload hardware to be mount on the U-CAT robots, specially designed to acquire data about shipwrecks. Results of the hardware selection activity is resumed in Deliverable D4.1 - *Report about functional specifications of the data acquisition and integration system*.

- **T4.2 (Months 4-21) - Real-time algorithms for on-board attentive sensory data analysis and task**: this task, started on the 4th month, encompasses the design and the development of the on-line algorithms aimed at processing acquired sensory data directly on board of the vehicles. Partners involved are UNIFI, dedicated to the analysis of optical data, CNR-ISTI, for the acoustic data processing, and TUT that worked on the data acquisition for the U-CAT robots. HWU cooperates to the task activities on the definition of the expected output to be given as input to the High Level Control (HLC) system. Regarding the optical data processing, two kinds of software have been developed: a Simultaneous Localization And Mapping (SLAM) system to aid the inspection vehicle for its self-localization during the mission, and an Attentive Analysis software to detect areas of interest. The use of both software provides to the HLC information about interesting areas, together with an indication of the their positions. As byproduct, a rough 3D representation of the environment is carried out by the SLAM software. Concerning the acoustic data analysis, algorithms for the identification of areas of interest run on both the search and inspection vehicle: while the search AUV observes a large area so to have a quick overview of the environment, the inspection vehicle scans smaller areas so to be able to detect finer details of the environment. A detailed description of the activities carried out in T4.2 is presented in deliverable D4.2 - *Real-time algorithms for on-board attentive sensory data analysis*. This document is composed of different sections, two of them representing the main contribution of task T4.2. One of the sections is dedicated to "On-board visual data analysis" whereas the other one to "On-board acoustic data analysis". Adopted algorithms are described for both the typologies of acquired data.

- **T4.3 (Months 10-27) - Post-processing scene reconstruction and object recognition**: in this task offline algorithms to produce results to be presented in the fruition software (WP5) are developed. Involved partners are UNIFI, CNR-ISTI and HWU. T4.3 has started the 10th month and concluded at the 27th month. The optical data recorded during the mission can be further analyzed by the developed software to obtain three main results: an accurate photo-mosaic that resumes the whole video footage in a single image (not included in the Description of Work but requested by the AAG), a dense 3D reconstruction of the environment through the employment of laser-based active triangulation method and a finer recognition software that re-analyses the optical data to detect artifacts and anomalies not found during the exploration. Similarly, acoustic data are further exploited to obtain both 3D data of the environment and more accurate detection results. Finally, 3D results from optical and acoustic data gathered during repeated missions on the same area are fused in an unique representation that describes not only the geometry of the scene but also its evolution over time (4D map) highlighting structural changes of the sea-bottom. In deliverable D4.3 - *Post-processing scene reconstruction and object recognition* a detailed description of the implemented offline algorithms is given. In addition to the preliminary laboratory testing results obtained through the proposed techniques, the outcome of real environment data process is proposed both in the optical and in the acoustic case. Different intermediate testing campaigns have been performed also with the aim of obtaining realistic data on which tuning and developing algorithms before the final demonstrations.

In deliverable D4.4 - *Change Detection Methods in Mapping Data for Site Monitoring* the 3D fusion and change detection algorithms is presented; detected changes in scenes are here represented with as colored 3D score map, where red areas indicate detected changes.

SIGNIFICANT RESULTS

The outcome of T4.1 are detailed reported in deliverable D4.1 - *Report about functional specifications of the data acquisition and integration system*. In particular, the most significant achieved results are (all in the first period):

- Definition of the optical payload hardware that includes two synchronized RGB cameras in stereo configuration with at least resolution of 800x600 pixel (to be installed in water-proof housing made by AMT), multiple high-intensity illuminators with low power consumption and a water-proof laser stripe projector. In addition, the vision module includes also a high-end Single Board Computer to run the on-board data analysis on the MARTA vehicle. In particular, in a preliminary phase, the Manta G-046 GigE cameras, the Bowtech AquaVision LED-800, the OceanLaser-L and the SBC Commell LS-378 have been selected.

- Detailed review of available acoustic payload for the search and inspection vehicle. A Side Scan Sonar is mounted on the search vehicle to cover large areas, whereas a multi-beam sonar is mounted on the inspection vehicle.
- Definition of the payload hardware for the U-CAT vehicles with particular attention to the overall cost. In particular a single Point Grey Chameleon camera together with high-efficiency LED illuminator and a Raspberry Pi processing unit is used.

Results of activities related to task T4.2 - At the Mid-term deadline, major results were:

- Design and development of a Simultaneous Localization And Mapping software: exploiting a stereo setup, high accuracy motion estimates are carried out even for long paths. Moreover a rough 3D representation of the environment is produced as a byproduct.
- Design and development of the Attentive Software able to detect area of interest.
- Design and development of software for the analysis of acoustic data gathered from both the search and inspection vehicle.
- Design and development of the acquisition system for the U-CAT vehicle.

Further results achieved during the second period of the project include:

- Testing and validation of the on-board visual data analysis on realistic images acquired during dedicated missions.
- Testing and validation of the on-board acoustic data analysis on realistic images acquired during dedicated missions.

Results of the activities related to task T4.3 - *Post-processing scene reconstruction and object recognition* are presented in deliverable D4.3 - *Post-processing scene reconstruction and object recognition* and D4.4 - *Change Detection Methods in Mapping Data for Site Monitoring*. Preliminary results the achieved within the mid-term deadline are:

- Prototype version of the mosaicking software, currently developed in Matlab and tested on an underwater monocular sequences. The algorithm is able to deal with parallax effect (given by the non-perfect planarity of the scene) avoiding the introduction of image artifacts.

Further results achieved during the second period of the project include:

- Testing and validation of the off-line visual data analysis algorithms including underwater mosaicing, dense 3D reconstruction and object recognition.
- Testing and validation of the off-line acoustic data analysis algorithms including construction of large scale maps and 3D acoustic bathymetry estimation.
- Definition of multi-layer images for optical and acoustic data fusion.
- Testing and validation of change detection methods.

ISSUES, DEVIATIONS FROM ANNEX I AND USE OF RESOURCES

During the first part of the ARROWS project, some deviations from the Description of Work, and even respect to preliminary choices, have been made.

- The selected optical hardware has been changed: two BASLER

ACE2040 cameras have been acquired instead of the Manta G-046, the illuminators are built directly by UNIFI and an OceanTool C-Laser has been chosen in place of the OceanLaser-L. Regarding the processing unit a Commell LS-37B (improved version of the LS-378) has been purchased.

- A mock-up version of the MARTA vision module has been also realized before completing the construction of the whole AUV. This way, the first tests of the vision payload and algorithms could be carried out independently with respect to tests on the mechanical, control and communication systems.
- Under explicit request of the AAG, the mosaicking software development has been added to the activities to be carried out in task T4.3.
- No more deviations were necessary during the second period of the project.

2.1.5. WP5 - Tools for fruition of archaeological items and sites

SUMMARY, TASKS AND OBJECTIVES

WP5 is the work package dedicated to the tools, developed in the framework of the project, aimed at the fruition of the archaeological knowledge including both the information obtained through the ARROWS system and the previously available one. It includes the implementation of a database capable of collecting and managing historical, artistic and archaeological data, with differentiated access (private/public) for the protection of data linked to the security of sites and artifacts. An information system was developed to integrate information coming from different sources in order to facilitate the spread of the knowledge and to simplify the access. Moreover, in order to improve the way of fruition of the knowledge from the user, an interactive mixed reality environment for virtual exploration was created. This is the only activity of WP5 that started during the first half of the project and it is object of the task T5.2, with the release of a first version within the mid-term deadline and the release of the final result in spring 2015. The activity related to the different WP5 tasks is here in the following summarized:

- **T5.1 (Months 19-33) - Development of a database and filing of information:** The goal of task T5.1 was the development of a database capable of collecting and managing historical, artistic and archaeological data knowledge including both the information obtained through the ARROWS system and the previously available one. Starting from the experience of archaeological partners of the project (DBCIS and EMM) – *Deliverable D5.1 - Archaeological database* – a database format as a part of the ARROWS information system for the management of multi-source heterogeneous data has been proposed. Details are provided in *Deliverable D5.4 – Information system for the management of multi-source heterogeneous data*.
- **T5.2 (Months 13-33) - Development of an interactive mixed reality environment for virtual exploration of archaeological sites:** This task was aimed at the implementation of an interactive mixed reality environment able to give to the general audience the possibility of virtually navigate among 3D reconstructions of artifacts obtained thanks to algorithms and techniques of processing based on optical and acoustic data collected through the payload sensors on autonomous vehicles. The first result of the task is the implementation of the environment that is populated through 3D models obtained thanks to the mission performed by the ARROWS vehicles. A first release of the environment was already achieved during the first project period: the Deliverable D5.2 - *Mixed reality environment for virtual exploration of archaeological sites – first release* describes it including both the ways of reconstruction and of fruition. In particular, the 3D

reconstruction of a small object has been obtained through computational vision algorithms based on data obtained through a system, exploiting a laser fan and a pair of cameras, similar to the one mounted on MARTA. The model of the object has been included in the virtual environment. The effort dedicated to the task T5.2 within the second period of ARROWS led to the final version of the mixed reality environment, made also available on line at the link: http://arrows.isti.cnr.it/MVE

3D navigable reconstructions of underwater archaeological artefacts obtained thanks to the missions carried out during the final ARROWS demonstrations are available under the "Media Center" tab of the project website www.arrowsproject.eu

- **T5.3 (Months 25-33) - Design and development of an information system for the management of multi-source heterogeneous data:** The main tool for archaeological data fruition developed within the ARROWS project is an information system capable of managing multi-source heterogeneous data obtained through the performed missions and the ones previously available. The ARROWS informative system is in charge of merging data captured by employing advanced technologies for the seafloors survey as well as data coming from historical, artistic, archaeological and documentary sources. Every expected typology of data has been carefully analyzed in order to implement a system able to properly capture and integrate all the available information. *Deliverable D5.4 - Information system for the management of multi-source heterogeneous data* summarizes the characteristics of the developed system including a brief review about the current state of the art in terms of data management and technologies concerning systems for knowledge representation.

SIGNIFICANT RESULTS

Significant results achieved in the framework of WP5 at the moment of the mid-term deadline are here in the following reported; they are related only to task

T5.2, the only one begun during the first half of the project:

- Virtual environment ready to be integrated with model of the environment and 3D reconstruction of artifacts;
- 3D reconstruction techniques based on laser fan and two cameras in stereo configuration successfully tested and in air in laboratory;
- Full compatibility between virtual environment and 3D models, based on standard formats, successfully tested and verified.

Further results achieved in the second period of ARROWS are:

- Analysis of the state of the art about available databases for archaeological information storage;
- Definition of an archaeological database to be integrated with the project system information;
- Definition of an information system for the management of multi-source heterogeneous data;
- Mixed reality environment for virtual navigation on underwater archaeological sites reconstructed through data acquired by the vehicles.

ISSUES, DEVIATIONS FROM ANNEX I AND USE OF RESOURCES

No issues or deviations from the Description of Work exist for Work Package 5.

2.1.6. WP6 - Testing Activity

SUMMARY, TASKS AND OBJECTIVES

The aim of the Work Package 6 of the project mainly includes three activities:

- Dry and bench tests on single elements and on assemblages (in a hyperbaric chamber if needed);
- Tests at sea in shallow waters in order to verify the abilities and

performances of the vehicles;

- Archaeology oriented tests to verify the performance of the vehicles during a preliminary testing mission in a realistic archaeological scenario purposely prepared.

To summarize, the related tasks are: Task 6.1 – Dry and bench AUV test, Task 6.2 – Tests at sea and Task 6.3 – Archaeology oriented tests. T6.1 and T6.2 were the only tasks partially distributed on the first project period and they were still ongoing at the mid-term deadline.

T6.1 (Months 7-24) – Dry and bench AUV test: the activity carried out in the framework of task T6.1 regards the preliminary tests on assembled components, sub-modules, and payload containers. Many components was already tested in pressure chamber and on test benches at the mid-term deadline. All the dry and bench AUV test concluded within the first two years of the project. This was a fundamental phase of the carried out work as represented by the considerable amount of 35 person-month on the related Deliverable D6.1 - *Dry-bench test report*. All the devices and the submodules to be integrated in the final system have been tested and the results are reported in D6.1 using a standard format that helped in the following development of the system and in the monitoring of the intermediate state of the activity.

T6.2 (Months 13-27) – Tests at sea: The activity dealt with shallow water test of vehicle maneuverability, speed, diving, sea-keeping, track-keeping and communication capability. Vehicles were singularly tested to evaluate the different capabilities and to individuate the aspects to be improved. Once the basics capabilities were achieved, also tests with multiple vehicles and on the communication system were organized. In particular some dedicated testing campaigns have been organized and performed as described in Deliverable D6.2 - *Sea test report.* E.g. in October 2014 several ARROWS partners performed a full week of jointed tests and a demonstration in the framework of the Breaking the Surface 2014 Workshop. D6.2 reports about other different testing campaigns performed and about the obtained results.

T6.3 (Months 19-30) – Archaeology oriented tests: The aim of this task of Work Package 6 was the preparation and the execution of the testing activity dealing with the underwater archaeology. Several good practice behaviors and configurations for the AUV missions, also as a function of the specific involved payload, have been identified thanks to this kind of tests. Moreover, the archaeology oriented tests permitted to fully understand the capabilities of the available sensors for archaeology data acquisition. Concerning optical payload, cameras and the illumination system (including LED illuminators and the laser line) were tested. Whereas about acoustics, the advantages of the use of different Side Scan Sonars, Multi-Beam Echosounder and a Sub Bottom Profilers were analyzed. Results are mainly reported in Deliverable D6.3 – *Archaeological oriented test report.*

SIGNIFICANT RESULTS

The outcome of the task T6.1 and the results achieved in its framework were achieved within the first half of the project:

- Tests in pressure chamber of the A_Sized AUV;
- Tests in pressure chamber of MARTA Vision Mock-up (the first vehicle

module);

- Tests in pressure chamber of the camera casings;
- Bench tests of the buoyancy modules for MARTA;
- Optical payload dry experiment in laboratory;
- Other wet tests (in a not pressurized environment) have been already made on on-board sensors: in particular, IMU, GPS, DVL and Multibeam sonar have been successfully tested in March 2014, in Roffia Lake, close to Pisa, Italy, to obtain the bathymetric profile of the lake.

Results achieved within Task T6.2 are the outcome of the sea trials and ad-hoc experimental campaigns; they include:

- Functioning test in water of all the system sub modules and components;
- Communication system validation;
- Elementary behaviors and basic maneuverability of the vehicles verified in water;
- Functionality tests on payload sensors as stand-alone devices and mounted on the vehicles;
- Capability of completing a full mission in sea in controlled environment (shallow water, protected from rough sea conditions) demonstrated.

Task T6.3 was oriented to the verification of the system capabilities oriented to the underwater archaeology and to the identification of the settings for all the involved devices in order to optimize the performance from an archaeological point of view:

- Acoustic and optical available payload tested on well-known archaeological sites;
- Identification of the best payload parameter choice to maximize the archaeological result;
- Identification of the AUVs best reference trajectory properties to maximize the archaeological result.

ISSUES, DEVIATIONS FROM ANNEX I AND USE OF RESOURCES

Concerning WP6 there are no issues and no deviations from Annex I have to be reported.

2.1.7. WP7 - Dissemination and exploitation of results

SUMMARY, TASKS AND OBJECTIVES

Work Package 7 mainly dealt with the following activities:

- Organization of the dissemination activities;
- Creation and updating of ARROWS web portal, www.arrowsproject.eu ;
- Organization of two thematic International Workshops;
- Training sessions for the archaeologists to explain them and to make them familiar with the new developed technologies.

To summarize, the faced related tasks are: Task 7.1 – Dissemination/Exploitation activities, Task 7.2 – Web Portal for dissemination, coordination and management, Task 7.3 – Organization of two thematic International Environmental Workshops and Task 7.4 – Training of the archaeologists and definition of the best practice standards.

T7.1 – Dissemination/Exploitation activities (Months 1-36): the activity carried out in the framework of task T7.1 regards the organization of the dissemination activities along the entire duration of the project. Fact sheets and two professional "short videos" (a Mid-term one https://www.youtube.com/watch?v=HDntdCSmMFg and a Final one https://www.youtube.com/watch?v=BTD8_naYcV4) describing the main aims and the development of the project to the general audience have been produced, according to the DoW.
Moreover, to increase the visibility of the project to a wider public and to create a real-time interaction between people and researchers, useful Social Media have been opened and managed to better disseminate the project's activities, in particular:

- **YouTube Channel:** http://www.youtube.com/user/ARROWSProject
- **Facebook Page:** www.facebook.com/ARROWSProject
- **Twitter Channel:** @ARROWSProject https://twitter.com/ARROWSProject
- **Telly (ex TwitVid) Channel:** www.telly.com/ARROWSProject

A description of the planned dissemination activities can be found inside the dedicated Deliverable D7.1 - *Report on planning of the Dissemination activities* and inside the Deliverable D7.4 - *Brochure, fact sheets and video presentation*.

T7.2 – Web Portal for dissemination, coordination and management (Months 4-36): ARROWS website www.arrowsproject.eu has been established to provide wide dissemination of the results, public deliverables, papers and all the important information about the project.
The website, updated on the basis of the final achievements of the project, has a public section and a restricted/private one (according to the DoW).

The carried out Dissemination Activities, made by all the ARROWS partners, have been entered in the EC Participant Portal.
The description of the project website is inside the dedicated Deliverable D7.2 – *Web Portal*.

T7.3 – Organization of two thematic International Environmental Workshops (Months 25-36): according to the DoW, two thematic international workshops have been organized. The attendees mainly came from end-user institutions (Superintendence and Archaeological Conservation institutions, Coast Guards, other Public bodies), academic and research institutes, but also from high level policy makers.
The first Workshop was EMRA14, http://www.issia.cnr.it/wp/?page_id=3490
The Workshop was held at CNR, Rome, Italy, on 9th and 10th June 2014.

The second Workshop was held within the 18th ICOMOS General Assembly and Scientific Symposium - "Heritage and Landscape as Human Values", http://www.icomos.org/en/about-icomos/governance/general-information-about-the-general-assembly/18th-general-assembly-florence-2014
The Workshop was held in Florence, Italy, on the 10th of November 2014.

The detailed description of the project official Workshop is inside the dedicated Deliverable D7.3 – *Report on the organization of the two thematic International Workshops*.

T7.4 – Training of the archaeologists and definition of the best practice standards (Months 25-36): the activity, carried out within this task, aimed at training the archaeologists so that they will be able to use, in the best possible way, the tools available for them thanks to the project. Technicians explained to the archaeologists the best practice standards to be taken when using the innovative devices that ARROWS provides, in order to optimize their performance.

More info about this can be found in the Deliverable D7.6 – *Best practice standard report*, a document that includes all the best practice standards defined for each phase of a potential mission.

SIGNIFICANT RESULTS

The achieved results within the WP7 are here summarized:

- ARROWS Website www.arrowsproject.eu
- YouTube Channel: http://www.youtube.com/user/ARROWSProject
- Facebook Page: www.facebook.com/ARROWSProject
- Twitter Channel: @ARROWSProject https://twitter.com/ARROWSProject
- EMRA14 Workshop;
- ICOMOS2014 Workshop;
- ARROWS Factsheets;
- About 50 papers (at International Journal or International Congresses);
- Some articles in the Local Press;
- Many news concerning ARROWS online;
- Presentation and Dissemination activities to the public (as described in details on the ARROWS EC Participant Portal).

Concerning the organized Thematic Workshops:

The first Workshop is EMRA14, http://www.issia.cnr.it/wp/?page_id=3490

The Workshop was held in CNR, Rome, Italy, on 9th and 10th June 2014.

EMRA14 Workshop summarized the EU FP7 marine robotics research, and provided a platform for marine stakeholders to share their technological challenges. For researchers, EMRA2014 offered dissemination opportunities for existing works and highlighted new application areas for consideration in future work. For marine research stakeholders, EMRA2014 offered novel approaches to solve marine challenges, and a platform for directing future research threads.

The underlying motivation of this workshop was to increase the efficiency in orchestration and dissemination across EU marine research. We observed a close coupling between individual FP7 projects and their intended application audience, yet many of the technologies developed are applicable beyond their motivating problem. Currently, for a marine technology stakeholder to fully digest EU marine research requires attending too many overly technical and overly specific individual workshops. EMRA2014 condensed an exciting range of cutting edge research developments into a single manageable event. The involved EU FP7 projects were: CADDY, MORPH, PANDORA, and ARROWS.

The second Workshop was within the 18th ICOMOS General Assembly and Scientific Symposium - "Heritage and Landscape as Human Values", http://www.icomos.org/en/about-icomos/governance/general-information-about-the-general-assembly/18th-general-assembly-florence-2014

The Workshop was held in Florence, Italy, on 9-14 November 2014.

The ARROWS workshop at ICOMOS 2014 was dedicated to Knowledge, Protection and Management of Underwater Cultural Heritage. The workshop was an important occasion to discuss innovative systems such as those developed in the framework of the ARROWS project, highlighting new opportunities and suggesting good practices to companies, agencies and stakeholders involved in evaluation, protection, and management of Underwater Cultural Heritage (UCH). The aim of the workshop was, on the one hand, to illustrate the potential of innovative underwater robotic tools and ICT fruition technologies useful to discover, protect, monitor, and enjoy the UCH in its different aspects; on the other hand the workshop generated a statement about new technologies and practices.

ISSUES, DEVIATIONS FROM ANNEX I AND USE OF RESOURCES

Concerning WP7 there are no issues and no deviations from Annex I.

3. Project management

3.1. Consortium Management Tasks and Achievements

As regards Task T8.1 “General Management”, the Coordination Team was led by Professor Benedetto Allotta, the Project Coordinator, and it was composed by members of the University of Florence; particularly the team was composed by:

- Prof. Benedetto Allotta: Project Coordinator;
- Prof. Carlo Colombo: Deputy Coordinator;
- Alessandro Ridolfi: Assistant;
- Riccardo Costanzi;
- Cristina Dolfi: Administrative Assistant.

The Coordination Team worked for the fulfillment of the project objectives in accordance with the time constraints and budget. According to the DoW, the Coordination Team followed and solved these issues:

- Production of documentation and Deliverables, according to the deadlines;
- Organization of the kick-off meeting, regular technical meetings, and the final meeting according to the DoW;
- Financial management and link with the EU.

The project Coordinator took care of relations with other partners, and maintained frequent contacts with the EU and the POs, in order to quickly respond to the EC requests.

For what concerns Task T8.2 "Administrative Management", the staff carried out an activity of financial supervision and administrative management:

- The pre-financing and the mid-term amounts have been transferred to the beneficiaries;

- The beneficiaries have been informed and instructed about the expenses reporting procedures;
- The beneficiaries have been supported with the preparation of the Form C using the Participant Portal.

As concerns Task no. 8.3 "Technical Management", the main objective was to maximize the communication, the coordination and the cooperation among the various Work Packages. Two working groups have been established during the Kick-off meeting of the project:

- the VDG - Vehicle Design Group;
- the SIG – Software Integration Group.

These groups, composed of many researchers, focused on the technical issues to find appropriate solutions to overcome them. The two groups worked all along the project (36 months), organizing dedicated Skype Calls and personal meetings, writing their minutes and exchanging many emails to get all the partners updated as regards the technical point of view.

The VDG and SIG worked, of course, also together and managed the Deliverables organization (writing in advance to the involved partners to deliver the documents according to the deadlines indicated in the DoW). All the ARROWS Deliverables have been submitted on the EC website.

3.2. Occurred Problems and Solutions

None.

3.3. Changes in the Consortium

None.

3.4. Project meetings

All the project meetings are reported in the following table.

Date	Partners	Topics	Venue
From 11 to 12/09/2012	ALL	**Kick-Off Meeting**	University of Florence, Florence, Italy
28/09/2012	VEHICLE DESIGN GROUP	Preliminary discussion about AUVs technical specifications	Skype meeting
03/10/2012	SOFTWARE INTEGRATION GROUP	Definition of partner roles and on board hardware and software architecture	Skype meeting
From 11 to 17/10/2012	TUT + HWU	Software integration	Loch Earn, Scotland
29/10/2012	SOFTWARE INTEGRATION GROUP	Multi-vehicle architecture, communication, control system	Skype meeting
08/11/2012	VEHICLE DESIGN GROUP	AUVs architecture and definition of the Vehicle Design Working Groups	Skype meeting
28/11/2012	SOFTWARE INTEGRATION GROUP	Communication, cooperation and control + Modular vehicle (MARTA) architecture	Skype meeting
29/11/2012	TUT + AMT	Piston (buoyancy module) design details	Skype meeting

From 3 to 4/12/2012	UNIFI + EL + NESNE + HWU + CNR + AMT + TWI	**Internal Technical Meeting** (about AUVs architecture and propulsion system design)	Pisa, Italy
10/12/2012	UNIFI + AAG	Archaeology Advisory Group meeting	Pisa, Italy
17/12/2012	VEHICLE DESIGN GROUP	AUVs technical specifications and design of motors, motor drivers, battery preliminary selection	Skype meeting
04/01/2013 09/01/2013 04/02/2014 06/03/2014	NESNE + EL	Motor drivers for A_Sized AUV and Cleaning Tool	Skype meeting
19/03/2013	VEHICLE DESIGN GROUP	Battery analysis, BR design current state, AUV design current state, Cleaning Tool possible solutions	Skype meeting
From 11 to 12/06/2013	ALL	**Internal Technical Meeting – Month 9**	Ocean Systems Lab, Heriot-Watt University, Edinburgh, Scotland – UK
13/09/2013 21/10/2013 11/12/2013	TUT + AMT	Design and manufacturing details for main hull and structure of BR	Skype meeting
26/09/2013	EL + NESNE	Cleaning tool – activity planning	Skype meeting

11/12/2013	VEHICLE DESIGN GROUP	Updates about the current design and construction status of the ARROWS AUVs: MARTA by UNIFI A_Sized vehicle by EL U-CAT by TUT	Skype meeting
12/12/2013	SOFTWARE INTEGRATION GROUP	Communication, Software Integration, Optical payload, Motor drivers	Skype meeting

18/12/2013	UNIFI + NESNE	Updates about Cleaning Tool solution by NESNE	Skype meeting
24/01/2014 28/01/2014 11/02/2014 19/02/2014 26/02/2014	NESNE + TUT	Motor drivers for U-CAT	Skype meeting
09/01/2014 14/02/2014 21/03/2014	UNIFI + TWI	MARTA mechanical production	Skype meeting
From 13 to 17/01/2014	UNIFI + EL + NESNE + TUT	AUVs motor drivers + Cleaning Tool 1st prototype by NESNE	UNIFI MDM Lab, Pistoia, Italy
30/01/2014	TUT + AMT	Design and manufacturing details for fin motor modules of BR	Skype meeting
05/02/2014	SOFTWARE INTEGRATION GROUP	Low level and high level software, software integration, communication through acoustic modems	Skype meeting
12/03/2014	EL + AMT	Piston design discussion	Oceanology International 2014, London
From 29/04/2014 to 06/05/2014	UNIFI + HWU	Tests planning + Integration between communication and cooperation + High and Low levels control integration	Ocean Systems Lab, Heriot-Watt University, Edinburgh, Scotland – UK
From 05/10/2014 to 12/10/2014	UNIFI + TUT + HWU	Integrations tests, communication tests, autonomous navigation tests to prepare ARROWS final demos	Breaking the Surface Workshop 2014, Biograd na Moru, Croatia

08/01/2015	UNIFI + NESNE	Motor drivers discussion	Skype meeting
11/02/2015	UNIFI + CNR	Dissemination	Skype meeting
19/02/2015	UNIFI + NESNE	Cleaning tool discussion	Skype meeting
06/05/2015	UNIFI + TUT + HWU	Software integration	Skype meeting
20/05/2015	UNIFI + CNR	Technical meeting about the acoustic data post-processing	OCEANS'15 congress, Genova, Italy
20/05/2015	UNIFI + NESNE + AMT	Technical meeting about the watertight casing for the Cleaning Tool	OCEANS'15 congress, Genova, Italy
31/05/2015	ALL	Technical meeting during the first official demo	Trapani, Sicily, Italy
23/07/2015	ALL	**Final Meeting**	Tallinn University of Technology, Tallinn, Estonia

In the second period of the project, many info and decisions have been exchanged, shared and taken by emails.

3.5. Deviations

At the end of the project the main deviations from the original DoW are three:

- The development of a Cleaning Tool, instead of an Excavating one;
- The development and construction of 2 different AUVs (one designed by UNIFI and one designed by EL), instead of more copies of the same vehicle

prototype. The AUV prototypes are MARTA by UNIFI and A_Sized by EL;

- The development of a well working U-CAT prototype, instead of more copies of the same biomimetic vehicle.

Concerning the Cleaning Tool and the main AUVs prototypes: the Consortium already explained the related reasons in the Mid-term Project Report.

As concerns the development of a single well working U-CAT prototype (biomimetic robot): as far as the biomimetic robot is concerned, a solution with a novel four-flipper turtle-like robot has been developed. The biomimetic robot U-CAT is capable of moving in all the 6 degrees of freedom. Such a system has several advantages compared to traditional propeller-driven systems and a fish-robot type system developed previously in TUT. However, developing a new biomimetic actuation system has added multiple high risk activities to the design and manufacturing process. To get a desired performance of the actuation subsystem, far more design, prototyping, and testing iterations than initially foreseen were needed. As a first step, a miniature vehicle model has been developed and tested to evaluate the performance of the four-flipper design. Afterwards, a full scale design has been performed and the U-CAT built. Tuning the four-flipper locomotion has been a tougher task than foreseen with several iterations on various aspects of the design, including but not limited to: shape and dimension of the flippers, materials used, motors and drivers, low-level position control of each flipper, high-level control of the vehicle, dead reckoning by means of inertial navigation of a quite "oscillating" vehicle. This is not a complete surprise since the rather unconventional novel design of the four-flipper propulsion has all the features of a "high risk -- high gain" research activity.

Although the U-CAT has been very successful in its trials with agile penetration of submerged buildings in the Rummu Quarry (Estonia) https://www.youtube.com/watch?v=EbG1AE_Z7Nc , the effort spent by TUT in order to have it properly working has been more than foreseen. So the Consortium has decided not to build a second biomimetic robot and to concentrate the effort on having the U-CAT prototype #1 in good shape to be used in team with the other ARROWS vehicles.

It is worth to notice that building the biomimetic robot team is now quite a straightforward task that might be easily achieved as a follow-up of the ARROWS project.

Regarding this situation, i.e. a single U-CAT built but fully working, the Project Coordinator already asked to the EC a request of modification of DOW. The issue has been checked by the legal office and it was accepted: as a consequence Deliverable 2.9 "Biomimetic robot team prototype" is no longer requested (suppression of D2.9).

In order to summarize, ARROWS successfully dealt with the development of a team of new heterogeneous AUVs to support archaeologists in all the phases (mapping, diagnosing, cleaning, and monitoring) of underwater campaigns. The components of the system are easily deployable by a team of archaeologists during a mission with limited support by technicians. The archaeologists were trained to use the innovative tools produced in the framework of the ARROWS project.

Three classes of new AUVs were developed according to the archaeologists' needs and, even if at the prototype stage, demonstrated to be able to cooperate with commercial AUVs:

- MARTA AUV: MArine Robotic Tool for Archaeology – modular AUV, easily adaptable to the various types of mission according to its configuration;
- U-CAT – small biomimetic AUV, usable for shipwreck penetration;

- A_Sized AUV – small torpedo-shaped vehicle, easily manageable thanks to its reduced size and able to perform shipwreck penetration.

3.6. Changes to the Legal Status

None.

3.7. Project Website

The Project website www.arrowsproject.eu is up to date and created according to the description inside the dedicated Deliverable "D7.2 - Web Portal for dissemination purposes" (revised version submitted on the EC Participant Portal on June 4th 2013). The final results of the ARROWS official demos can be found on the Project website at: http://www.arrowsproject.eu/media-center/trials/ .

Project No: 308724
Project Acronym: ARROWS
Project Full Name: ARchaeological RObot systems for the World's Seas

Consolidated Review Report

Answers and Comments for the Reviewers

Date of submission: 25/03/2016

Project Coordinator name:
Prof. BENEDETTO ALLOTTA
Project Coordinator organization name:
UNIVERSITA DEGLI STUDI DI FIRENZE
Version: 1.0

First of all, we really wish to thank the Reviewers for their helpful suggestions. We would like also to thank the Reviewers for all their positive comments and for having appreciated the work performed by the Consortium.

In order to make clear our answers and comments we have adopted the following criteria: for each request of correction/clarification the corresponding answer is here reported and explained in bold (question & **answer**).

Q&A

A. In the words of the authors, "of the original testing plan - studying the archaeological sites with sonar, filming them, and constructing 3D models of them - approximately one third was completed". Nevertheless, the team has amassed considerable experience in the operation of autonomous vehicles and has clearly illustrated the enormous potential of the latter to simply the tasks involved in archaeological exploration.
Here are some related comments coming from the ARROWS archaeologists: we can say for sure that an AUV is a very useful platform for marine archaeologists. Of course, the AUV is just a vehicle, a platform carrying survey equipment. The quality of the information gathered depends on the quality of the surveying equipment. The side-scan sonars used during the Baltic Sea trials were high-quality and at the end of the fieldworks the archaeologists had georeferenced sonar scans taken from various angles and depths. Those scans are without doubt the best we have about the Citadel site.
The fieldworks at sea have two aspects – finance and time. Although an AUV can be costly to purchase, it makes the fieldworks at sea more time-efficient. In ideal case, a research vessel can deploy an AUV for mapping wider areas and at the same time perform various other tasks.
While the research vessel with towed side-scan sonar can be used only during the summer, small AUVs can be deployed also in the winter when the sea is frozen and ice strong enough. Such experiments were made in February 2016, when U-CAT performed under-the-ice missions. Winter is particularly suitable for robots equipped with cameras, because the water is clearer and with additional lighting, the visibility tends to be better than in summer.
The AUVs with the capability to hover – MARTA and U-CAT have proved themselves very useful, since they are capable of moving very close to the archaeological site without damaging it. This was proven by MARTA in Citadel site and U-CAT in mining-machine penetration test. The ability to gather close-up photos and video could be especially useful for assessing the state of preservation and damages to sunken objects. The full potential of both MARTA and U-CAT could not be used in Tallinn Bay due to poor visibility. The visibility problem may, at some extent, be avoided by adding additional light sources to AUVs or to deploy a hover-capable AUV equipped with lights.
In conclusion we can say that the underwater systems developed during the ARROWS project performed remarkably well. It was said that from the mission goals approximately one third was completed. Taken into account the constant bad weather during the trials and some technical difficulties this result should be considered quite satisfactory.

B. The results of the project illustrate the enormous potential of the technologies for archaeological exploration. In spite of the tremendous progress done in the scope of the project, the reviewers could not ascertain (from the absence of data acquired during tests in the water) if the U-CAT vehicle has indeed performed what would qualify as total shipwreck penetration.

During the official ARROWS trials the U-CAT did not perform an actual total shipwreck penetration mission. The penetration missions were first conducted in more simple conditions mimicking a simple shipwreck. For example U-CAT was used in AUV mode to penetrate the underwater constructions in Rummu quarry. It was also used in ROV mode to inspect and enter the submerged machinery. The initial goal was to validate the technology in these simpler conditions before conducting similar experiments in actual shipwrecks. Such decision was done as in simple conditions it was much easier to gather information about the technical abilities of the vehicle due to simpler logistics (high accessibility to sites, small depth and constant access to surface vessels). Thanks to simple logistics it was possible to run more experiments during a short demonstration period and a narrow suitable weather window. The goal was to move on to the total penetration mission after the Rummu tests, however some shortcomings were revealed in highly experimental custom sensor systems of the U-CAT. It was decided that these shortcomings have to be addressed properly before moving on to more complex conditions. After the Tallinn demonstrations and the official end of the project major improvements have been done to solve the revealed problems. The acoustic localization issues with the homing pingers and the modems have been mostly solved. Also major advances have been done with the motion control of the vehicle. Currently the vehicle performs in a much more stable manner both in AUV and ROV mode. The updated systems of the vehicle have been tested after the Rummu demonstrations during thorough pool experimentation sessions. The acoustic localization and the ROV auto-piloting has also been tested in natural conditions by penetrating the Rummu machinery in winter, through a hole in 20 cm thick ice layer. More rigorous tests, including the total shipwreck penetration will be conducted in summer 2016 as soon as the weather conditions are again suitable.

C. It is not clear to what extent the methodology proposed for underwater site inspection has been implemented across the “fleet” of vehicles used in the ARROWs project, effectively allowing them to work in cooperation towards meeting archaeology-relevant tasks”.

The reviewers are right and this is a justified question.

Concerning vehicles cooperation, MARTA demonstrated to be able to work well with commercial AUVs. E.g. the experimental results obtained during the Rummu quarry demonstration (July 20th - July 22nd) were achieved thanks to the collaboration within two of the ARROWS AUVs (the commercial IVER3 by OceanServer as Search-AUV and MARTA as Inspection-AUV). During a Searching survey based on the interferometric Side-Scan Sonar of the IVER3, two considerably big (some meters per side) unknown targets were identified in an area of the lake far from the most frequented one. Several optical images of the two targets were then collected during an Inspection mission performed by MARTA on the two identified spots. The optical Inspection mission was performed on the basis of the GPS points of the targets acoustically identified by the IVER3.

Concerning this specific topic, some technical papers will be published soon.

D. A specialized cleaning tool was designed and manufactured. The device was successfully tested stand-alone (some results are given in the Deliverable D6.2 – Sea test report), it was also mounted on an AUV but because of the weather conditions during the final demos (in particular strong currents) the consortium decided not to test it in open waters for safety reasons”. Some form of feedback from the archaeologists regarding the utility of the tool developed seems to be missing.

Here are reported some brief comments from the archaeologists belonging to the Consortium (please consider that, at the moment, the device has been tested only stand-alone): “Up to now, usually in case of shallow waters and small artefacts cleaning operations are done by divers. Concerning the developed cleaning tool, it seems a good idea and definitely worth developing and testing but it is probably more suitable for Mediterranean scenarios, since there are sunken settlement sites on the Mediterranean seabed with lot of small artefacts.” Moreover: “The integrated system (cleaning tool) carried out by NESNE is useful in research, protection and valorisation of underwater cultural heritage. This system can be used for making partial excavations in order to bring out not identified structures or objects lying in the seabed. Objects can be hence studied in the aim to identify their chronology, their function and their consistence. This system is really useful because it, reducing the research on wrecks and submerged structures made by divers, contributes to decrease their risks. Furthermore, the costs of diving are minimized and the analysis and control on underwater structures times are reduced. The system can be well applied on sandy or muddy or stone seabed. The managing and handling of underwater equipment like cameras, bollards etc. can be realized as well by the system.”

<u>As concerns the Rejected Deliverables</u>:

Deliverables D 1.5, 2.6, 4.2, 5.3, 6.3 and 7.6 have been rejected and should be revised according to comments sent in the email 'Final Scientific and Technical Review of ARROWS project 308724 - Review' (Ares number: (2016)1159543) and its attachment.

D1.5 - The new version of deliverable D1.5 includes, as answer to reviewers' comments, some additions: in particular, a clearer costs evaluation has been performed to highlight the advantages of the developed ARROWS technologies.

D2.6 - The new version of deliverable D2.6 includes, as answer to reviewers' comments, some feedbacks from the archaeologists regarding the utility of the developed cleaning tool. These comments are reported at the end of the "Conclusions" section.

D4.2 - The new version of deliverable D4.2 includes, as answer to reviewers' comments, a new paragraph related to suitable "Conclusions". We apologize this section was previously missing.

D5.3 - The new version of deliverable D5.3 includes, as answer to reviewers' comments, some diagrams, figures, or photos illustrating the functionality and types of outputs that can be obtained using the developed software suite. A version of this suite can be directly downloaded from the link present within the Deliverable.

D6.3 - The new version of deliverable D6.3 includes, as answer to reviewers' comments, some additional sentences included inside paragraph 5 "Test results and Conclusions".

D7.6 - The new version of deliverable D7.6 includes, as answer to reviewers' comments, some additional sentences included at the end of paragraph 3 "Archaeologists training" and within paragraph 4 "Best practice".