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UPGRADE and IMODELASER: Tools and Best Practice for 3D Data Acquisition and Processing for CH in Different Environments

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Abstract

The acquisition and processing of 3D data for the documentation of cultural heritage objects is gaining more and more importance. 3D models do not only serve as a valuable means for visualization and presentation of objects, but also represent a form of digital preservation and can additionally serve as a basis for archaeological or architectural analysis. The two NEWTONs IMODELASER and UPGRADE deal with this task by developing practices and tools for efficient data gathering and 3D documentation. While IMODELASER aims to optimize terrestrial image-based 3D modelling by means of integrating terrestrial laser scan data, e.g. of buildings or other medium scale objects, UPGRADE concentrates on data gathering and representation of underwater sites.

1. Introduction

In EPOCH Work Package 3, after identification of missing tools in the processing pipeline, various "New Tools Needed" (NEWTONS) were defined to be developed and implemented. Two of these tools, UPGRADE and IMODELASER, deal with 3D data acquisition by means of combinations of different types of sensors and under different environmental conditions. IMODELASER concentrates on 3D modelling based on terrestrial images and laser scanning, aiming for an optimization of the obtained models by exploiting the strengths of both sensor types in order to overcome their specific weaknesses. These are mainly the weakness of automatic image matching techniques when dealing with homogeneously or repetitively textured surfaces and the inaccuracy of laser scan point clouds in terms of edge modelling. Therefore, in IMODELASER we aim for a combination of edges measured in images and highly dense point clouds for homogeneous surfaces yielded by laser scanning. As for IMODELASER in the terrestrial case, UPGRADE concentrates on 3D models but data gathering and representation are related to underwater sites. UPGRADE aimed for a widely automated generation of 3D models from underwater video, acoustic and navigation data. The output of the project was not only to automate the procedures of data gathering as far as possible, but also to improve the quality of the resulting, photo-realistic 3D models by combining the state of the art of underwater measurement instruments with suitable hardware and software. The problem concerns the design, test and development of a set of tools and best practices for collecting data from underwater archaeological sites by employing robotic vehicles and automatic devices under the supervision of archaeologists and engineers, possibly in cooperation, under some circumstances, with divers. The kind of data to get while navigating consists, essentially, of a set of georeferenced pictures in photogrammetric quality in order to construct a 3D model of the explored area in a virtual environment with a specified level of precision. This paper also presents how UPGRADE tools can be compliant with other NEWTON projects specifically presented in the terrestrial CH environment.

2. IMODELASER - Combining photogrammetry and terrestrial laser scanning

Within IMODELASER, we aimed for a widely automated generation of 3D models from terrestrial images and laser scan data. The goal was not only to automate the procedures of data processing as far as possible, but also to improve the quality of the resulting, photo-realistically textured 3D models by combining the strengths of the two, in our case complementary, sensors deployed, namely digital still video cameras and terrestrial laser scanners, in order to overcome the specific weaknesses of each single sensor. The weakness of pure image-based 3D modelling consists of the fact, that automated image matching procedures, which are required to measure homologous points in two or more images to obtain accurate image orientations in a first step and 3D features which model the object in a second step, are error prone especially in homogeneous areas with low texture information. The consequences are no or wrong point measurements which then have to corrected manually. Contrarily, laser scanners have the capability to generate very dense 3D point clouds on such homogeneous areas, nevertheless they lack in terms of accuracy for 3D modelling of linear features, especially edges. Edges in turn can be extracted, partly automatically, from images with high accuracy. Therefore, IMODELASER aims for a procedure which uses the images for edge extraction, laser scanning to generate highly dense 3D point clouds and then, after automatic outlier removal, accurate co-registration of images and laser scan data and re-triangulation of the 3D features, determines a 3D model that represents the object highly accurate. For the demonstration of the capabilities of the developed and implemented algorithms, the ETH-Sternwarte, built in 1864 by Gottfried Semper in Zurich, was selected as a showcase object and modeled by means of our developed tools.

2.1. 3D surface reconstruction using laser point cloud and image data

3D surface reconstruction using point clouds from laser scanners is one of the practical approaches for surface modelling. It has to be conducted to generate a piecewise linear approximation of the object's surface. However some deficiencies of the data obtained by laser scanners , e.g. object boundaries, and the needs for automation of the modelling process make the potential for the employment of other sources of data.

If the sampling requirements are satisfied during scanning, point clouds obtained by laser scanners, including the geometry and the implicit topology, are used to reconstruct the object surfaces by triangular meshes [†]. Since the objects we are dealing with have a three-dimensional geometry and inherently the geometry of the point cloud, 3D triangulation of the point cloud is required. Although the 2.5D Delaunay triangulation gives a partial solution, it yields an incorrect topological surface model. Thus, surface reconstruction by a 3D Delaunay triangulation followed by surface extraction from the volumetric convex hull has to be performed. However, cleaning the point cloud from outliers is necessary prior to surface reconstruction

In this section we explain briefly a possibility to integrate edges from image measurements with point clouds from laser scanners to approach to a more complete surface model. The first subsection presents a method to clean data from errors and the second subsection explains the surface reconstruction and edge integration process briefly.

2.2. Outlier detection

Cleaning laser scanner point clouds from erroneous measurements (outliers) is one of the most time consuming tasks that has to be done before modelling. There are algorithms for outlier detection in different applications that provide automation to some extent but most of the algorithms either are not suited to be used in arbitrary 3 dimensional data sets or they deal only with single outliers or small scale clusters. Nevertheless dense point clouds measured by laser scanners may contain surface discontinuities, noise and diffrent local densities due to the object geometry and the distance of the object to the scanner; Consequently the scale of outliers may vary and they may appear as single or clusters. In [Sot07] we have proposed a clustering algorithm that approaches in two stages with the minimum user interaction and input parameters while it can cop with different scale outliers.

In the first stage the algorithm removes relatively large scale erroneous measurements and in the second phase it detects and removes the outliers that might not be as large as the first ones but according to the scanned object surfaces they are considered as wrong measurements. The algorithm has unconstrained behavior to the preliminary knowledge of the scanned scene and it does not suffer from the varying density of the points. The algorithm efficiency is assessed by a test on a simulated point cloud, which contained single and clustered outliers. The assessment is done with respect to a manual separation of outlier/inlier points. The type I and type II errors are estimated and the results are reported. In addition some examples in terrestrial laser scanner point clouds are presented and the behavior of the algorithm on the data sets are shown and discussed. Results show that the algorithm detects single and even clustered outliers almost without user interaction. Also, in case that the user editing is required, the result of the algorithm provides easier editing procedure due to the selection of point clusters rather than individual points. Some examples of the results are depicted in Figure 1.

2.3. Registration

Registration of images taken by CCD array cameras with respect to point clouds obtained by active sensors like laser scanners is necessary prior to the integration of the both data sets (texturing, overlaying, gap filling, etc). This is mostly done by the use of some targets visible in both data sets or by preliminary laboratory calibration, while the camera is mounted on the active sensor (e.g laser scanner). Nevertheless, there are various cases in which there are no common targets between the two data sets or the pre-calibration is not possible due to either using not mounted cameras or different acquisition times. Additionally, in case common targets are used, the mapping function that maps the point cloud to the image coordinate system is obtained over targets, thus the accuracy of the function is very much dependent on the distribution of the targets. More over, in case of pre-calibration, the calibration parameters may not remain stable if the camera has been dismounted for some movement purposes. Therefore a kind of on the job registration would be useful.

By orienting images with respect to an existing point cloud system it should be possible to see what improvements can be done when combining point cloud data obtained with different measurement techniques. We assume that the rough orientation parameters of the images are available in an arbitrary coordinate system. These parameters serve as approximations for an automatic process that incorporates a point cloud obtained by a laser scanner or a similar active sensor. By back projecting the points of the laser scanner point cloud into the images, the orientation parameters can be improved, by iteratively moving the two point clouds in a way that the distances between those two become minimal. As a result more precise orientation parameters are obtained, which in turn can be used to improve the existing point cloud with respect to edges and outliers that usually are present in point clouds from laser scanners or similar active sensor devices.

[†] Methods which use parametric sold shapes (plane, sphere, etc.) to perform object extraction are not referred here since this paper is about objects with arbitrary geometry

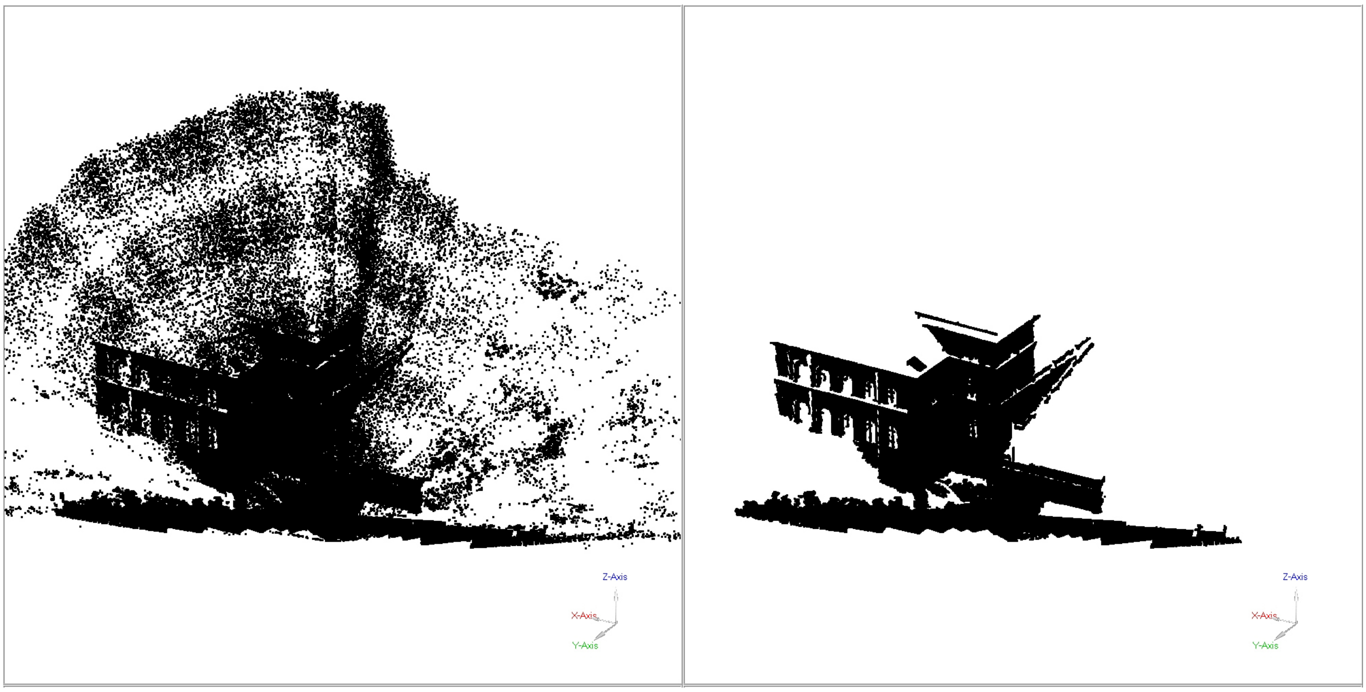

Figure 1: *Results of applying the proposed outlier detection algorithm on some scans of the Sternwarte building which are captured by Faro laser scanner. Left image shows raw point cloud and the right image shows the cleaned point clouds after applying the algorithm.*

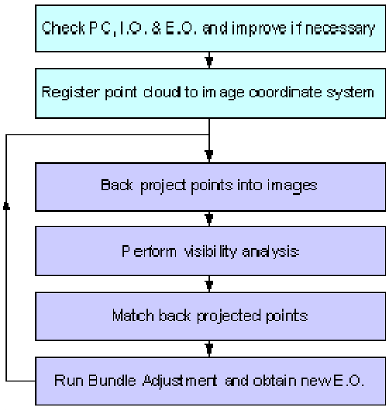

Figure 2: *Workflow of the registration procedure*

The data is divided into two data sets. One set is a dense point cloud that was obtained with a laser scanner. The other dataset consists of images taken of the object as well as measurements in the images. With the measurements an exterior orientation has been calculated with Photomodeler and as of such a sparse point cloud has been obtained. Figure 2 shows the suggested workflow of this task. The first two steps are considered pre-processing steps and are done manually. In a first step the point cloud has to be checked if gross outliers are present. If this is the case those have to be removed. Additionally the interior and exterior orientation parameters have to be checked and improved if they are not good enough. Then the laser scan point cloud has to be registered to the image coordinate system. The laser scan point cloud is rotated and scaled into the coordinate system of the photogrammetric point cloud. By doing so the photogrammetric point cloud remains fixed and the orientation parameters can be used for further steps. Afterwards the main processing chain is started, which mostly consists of automated modules:

- Backprojection of the laser points into the images
- Visibility analysis to reduce probability of mismatching
- Matching of the points

Two C++ tools are used which incorporate these three steps - the first tool is performing back projection and visibility analysis while the second one is doing the matching part. Two matching algorithms were implemented: cross-correlation and least squares matching [Gru]. Once the matching is finished, the matched points can be used as measurements for the bundle adjustment, which is performed with an external tool. After the bundle adjustment is completed successfully a new interior and exterior orientation of the images can be obtained. If the new orientation is acceptable the process can be stopped. If it is not then the points have to be projected back into the newly orientated images and the same procedures have to be performed again until the results are satisfactory.

The goal of this procedure is to have the images orientated precisely to the laser scan point cloud. By doing so the information of the images can be used to improve the model acquired by the laser scanner. Edges for example can be easily extracted from images. Since laser scanners do not perform well on edges the edge information can be transferred to the triangulation algorithm in order to have a better representation of edges in the final model. Another application is to perform outlier and blunder detection. By using the edge information it should possible to remove not only gross outliers but also blunders.

2.4. 3D Surface reconstruction

Having removed outliers, the point cloud is ready for surface reconstruction. First step is three dimensional Delaunay triangulation (Delaunay tetrahedralization). Unlike the two dimensional Delaunay triangulation which provides a surface mesh, the direct result of the Delaunay tetrahedralization (DT) is not a surface but a convex volume that surrounds the surface. Therefore the surface must be extracted using an additional procedure (3D surface reconstruction).

3D surface reconstruction from the 3D convex hull is an open problem even in computational geometry communities. Here, we have employed the most advanced approaches and we've contributed to the improvement of the approach using a neighborhood graph. The approach is based on the pruning of the initial surface model obtained by the extraction of the Gabriel graph from the 3D volumetric convex hull. The pruning is done in several steps based on topological relations, 2D manifold properties, a proximity graph, EMST (Euclidean Minimum Spanning Tree) and a neighborhood graph, KNN (K-Nearest neighborhood), followed by a hole filling process. Although the implemented approach is not a complete solution of the problem, it shows interesting results. One should notice that most of the process is done automatic and with the minimum user interaction. In addition no threshold or predefined value is required.

To get advantage of 3D edge information (from images) in the object reconstruction procedure, an edge-constraint 3D triangulation followed by an edge-constraint surface reconstruction algorithms are implemented. Since the surface reconstruction algorithm is based on the Delaunay properties of the prior 3D triangulation step, preserving these properties had to be considered. A constrained Delaunay tetrahedralization which has provably good boundary recovery is introduced by [Sch02], however a constrained three dimensional surface reconstruction algorithm is not well covered by the current literature. Following his algorithm, the surface reconstruction algorithm is modified so that it can accept the 3D edges as constraints in the process. The modification is done in both convex volume generation and the surface extraction process. The ultimate result is a surface that in the defined 3D edges it respected the 3D edges and avoid wrong interpolation in edge areas (see Fig. 3).

2.5. Availability of the tools and conclusions from IMODELASER

The developed software consists of several standalone programs for the described processing steps. The input data on the one hand are 3D laser scan point clouds in ASCII XYZ format - other formats can be converted to this - and on the other hand oriented images - meaning that the coordinates X, Y, Z of the perspective centers of all involved images and the spatial rotation angles Ω, Φ, κ are known with respect to a common coordinate system - and measured 3D edges (OFF format). Currently, we investigate if parts of the software can be integrated into MeshLab (CNR Pisa), e.g. outlier detection and re-triangulation, to make them available also for further purposes. To make the developed workflow available, we opt to provide a service in terms of consulting and processing due to the facts that the photogrammetric processing requires expert knowledge from the data acquisition to photogrammetric processing and assessment of the results. Depending on the experience of potential users, different levels of support from our side can be offered. Regarding the developed method, a clear improvement of 3D edge modelling by means of triangulated surfaces could be demonstrated. The successful combination of image-based and range-based modelling opens new options for but also beyond cultural heritage documentation, e.g. when applied to aerial images in combination with airborne laser scanning. Though the developed tools partly still require long processing times, e.g. the registration of the images with respect to the laser scan point cloud, modelling quality can significantly be improved. Furthermore, there are options for speeding up the procedure by optimization of the programmed code. IMODELASER, or at least parts of the developed tool chain, can serve as one possible method for 3D data acquisition and modelling for other NEWTONs, e.g. 3DKIOSK and UPGRADE.

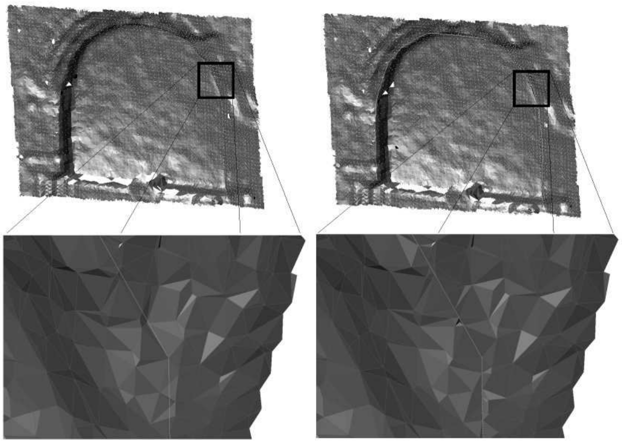

Figure 3: *Result of applying 3D edge constraint in the explained surface reconstruction process. Left images show surface without the constraint and the right images show the reconstructed surface after applying the 3D edge constraint (the line in the edge of the niche).*

3. UPGRADE - Underwater photogrammetry and archaeological data enhancement

Over the last ten years, we have seen significant study in the development of efficient subsystems for underwater applications. This has been specifically driven by the offshore industry and European Commission in term of IT, research and new tools investment. Over the past decade, however, with the growing challenge of reaching deeper sites, human divers are being complemented with or replaced by Remotely Operated Vehicles (ROVs). These ROVs are equipped with sonar and vision equipment and, if required, tools to sample the seabed and manipulate artifacts. Regardless of how data are acquired, the crucial problem of overlaying the different data sets to generate composites of the interested site at both large and small scales has not yet been satisfactorily resolved. No off-the-shelf tools are available for these purposes. Several issues have not been satisfactorily addressed in the scientific literature and no efficient software tools are available to solve them. UPGRADE addresses an efficient way to equip a small class commercial robot in survey, for virtual reconstruction, of a geo-referenced portion of the sea bottom taking care of installation and synchronization of needed commercial and efficient subsystems. During the project, preliminary tools to equip the ISME's ROV for gathering, integration and fusing acoustic, optical and platform navigation data in surveying a prefixed area is presented. These tools should make the entire process largely automatic, and facilitate the construction of geo-referenced 3D maps of underwater areas. Another issue discussed in the paper is the automated generation of underwater images for photogrammetric purpose and for integration of Digital Terrain Models (DTM) at different resolutions, associated with the corresponding navigational data. This paper highlights the state of research developed in the EPOCH network in order to facilitate safer, faster, and far more efficient ways of performing archaeological site surveys and 3D reconstruction. In the following sections we describe the tools and strategies used in virtual reconstruction of an archaeological underwater site: the survey methods, the calibrating procedures, collecting photographs using ROV and divers and 3D data output formats.

3.1. Two different techniques for data capture

The photogrammetric survey is usually made by a set of photographs with the right overlap (around 60The photographs are taken 60If the site is not too deep (usually up to 60m), it is possible to survey both with divers (CNRS partner) or with ROV (ISME partner) [CZSG]. In this project our divers use a Nikon$^{\text{TM}}$D200 digital camera with a 14mm lens from Sigma$^{\text{TM}}$and two flashes Subtronic$^{\text{TM}}$. The digital camera was embedded in Subal$^{\text{TM}}$housing with a hemispherical glass, the ROV was equipped with Nikon DH2 digital camera, a 14 mm lens from Sigma$^{\text{TM}}$and two flashes Nikon$^{\text{TM}}$, SB800. The housing was made by COMEX with a flat glass and connector and the ROV interface was provided with ISME. Before survey the site is usually explored by multibeam (IST partner) in order to obtain a wide low resolution map of the sea bottom. The site is structured with scale bars (2m) and a set of markers (concrete blocks 15x15x10cm) or ropes are used in order to made a visible grid or path. During the survey the concrete markers or ropes are surveyed by the ROV, strip by strip, in order to cover the entire archaeological finds area [CZS*]. With the ROV, the photographs can be taken in two modes:

- Manually, the operator, looking at the scene through the lens using a small video camera installed on the photo camera.
- With a fixed frequency, decided according to the flash recharge time, ROV speed and altitude.

3.2. Multimedia calibration

Camera calibration in multimedia photogrammetry is a problem that has been around and documented for almost 50 years [BR, UPG80, UPG95]. The problem is not obvious, the light beam refraction through the different dioptres (water, glass, air) introduces a refraction error which is impossible to express as a function of the image plane coordinates alone [Maa95]. Therefore the deviation due to refraction is close to those produced by radial distortion even if radial distortion and refraction are two physical phenomena of different nature. For this reason we start to use standard photogrammetric calibration software and make a calibration of the set housing and digital camera. The distortion corrects in a large part the refraction perturbation. This approach is strongly dependent of the ultimate dioptre water/glass of the housing. To try to minimize the refraction error we can find on the market some housing with a hemispherical glass, which is the case of Subal$^{\text{TM}}$housing used with the diver. The other one, made by COMEX, the glass is a plate and the refraction action is much more important. In the second mission of the project (Tremiti Mission - Italy), special care is taken calibrating the panel: CNRS study and test two different panels in order to better compensate separately refraction and distortion (see Fig. 4).

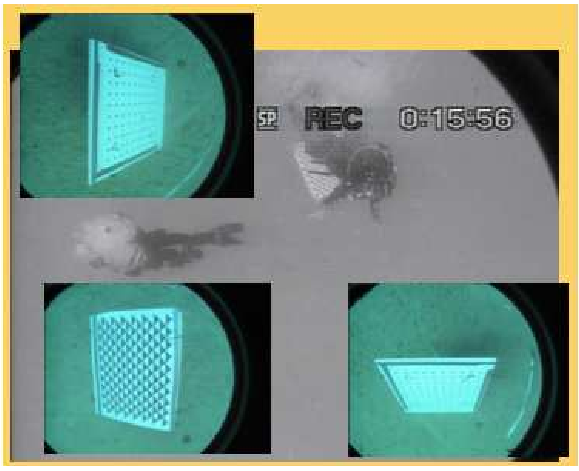

Figure 4: *Camera calibration procedure*

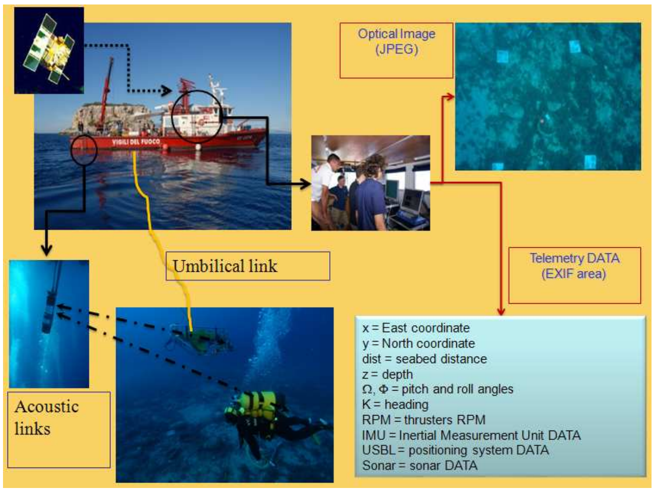

Figure 5: *Data capture system*

3.3. The tools for data capture

Based on the experience of the partners, during UPGRADE, two main systems are used to survey the sites: with an ROV or with divers. For ROV use, the main problem is to synchronize all data coming from different onboard sensors with the photograph command to the photo camera. One of the tools developed in the project is the EPL, a software library for generating georeferenced, enriched visual data from underwater photo and video. This software tool will generate EXIF postcards by associating acoustic, geographic and navigation data, acquired by the NGC system of the underwater robot, to photos and video frames. The software library can be included into NGC system of commercial ROVs and AUVs for JPEG/EXIF restitution of surveyed areas (see Fig. 5). During diver survey not all information can be synchronized, in particular the USBL system, which data are on the surface console, can be merged with information on the photo camera only after the end of the survey. A useful tool developed to enrich survey diverâĂŹs photograph is PUT, a small device to collect data during the flashing phase about photo camera orientation and acceleration. PUT (see Fig. 6) is a low cost device for underwater positioning and tracking of Divers.

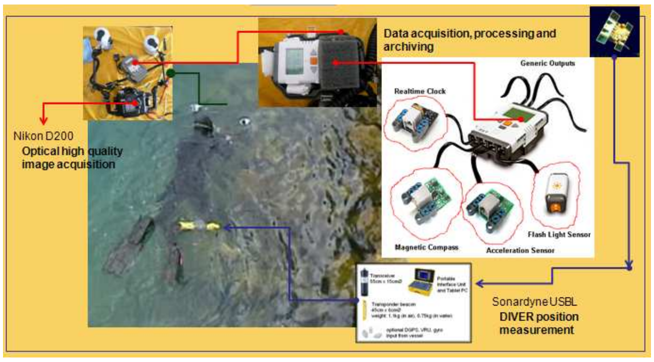

Figure 6: *PUT tool for data capture by divers*

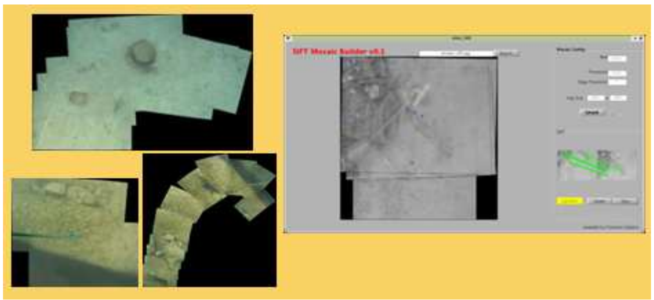

Figure 7: *SMuS tool for rapid mosaicing*

The device consists of a portable set of sensors, controlled by a microcomputer, for acquiring geographic and attitude data to complement photo and video surveys made by divers. Device construction is based on COTS and rapid prototyping methods. During the ROV survey or after the dive, with the data set coming from the tools developed, it is possible to view a partial reconstruction of the area with the photomosaicing tools SMuS. SMuS is a software suite for real-time photomosaicing from underwater photos and video frames of a surveyed area (see Fig. 7).

3.4. Site reconstruction

At the end of the survey, the data coming from the bathymetry mission, the photographic campaign and the archaeological knowledge of the artefacts are merged in virtual reconstruction of the 3D scene. All data can be stored in a relational database and a set of Java tools allows to wrap objects from the database and to produce a VRML or X3D representation. In the scene the seabed is textured using the oriented photographs. The textured seabed is obtained by triangulation of the points used to orient the photographs. UPGRADE has developed a tool to link each triangle to a set of possible photographs for texturing with the current used photograph mentioned. The result (3D points, triangle, oriented photographs) are written in XML with possible transformation to X3D and VRML. This way is very convenient to change the photograph used to texture a triangle or a zone. These data can be used to revisit the site for example with MVT. MVT provides marine cultural heritage professionals with the necessary tools to easily visualize and interact with bathymetric and other terrain datasets. It also provides pilots of Remotely Operated Vehicles (ROVs) to plan and visualize dives either offline or in real-time scenarios.

3.5. Conclusion

The UPGRADE project facilitates the construction of geo-referenced 3D maps of underwater archaeological areas. As in the other NEWTON projects, UPGRADE uses X3D and VRML representation but the data contained are different due to the environment characteristics and the instruments to measure the physical variables. At the end of the project we have the knowledge to relate some parts of underwater archaeology with what has been discovered and structured in other projects although it is not easy to have a common infrastructure between terrestrial and underwater data collection and representation. Because of the unique nature of the UPGRADE project, there is little overlap between the other NEWTON projects such as AMA, the context aware work of CIMAD, the avatars of CHARACTERISE and the AR visualization of 3DKIOSK. At the end of NEWTON and the EPOCH project, UPGRADE has provided a very specialised set of tools specific to the underwater archaeologist that also considers what the terrestrial scientist does and may have in mind for the future. A future opportunity, taking the advantage of new technology for underwater uses, is to join together both worlds starting from EPOCH results, best practice and tools.

4. Contact

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