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Survey and photogrammetry in underwater archaeological contexts at low visibility in the Venice lagoon

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ABSTRACT

Underwater archaeological research, survey, and documentation are influenced by environmental conditions, in particular for the photographic aspects. The last challenge of the underwater survey is the application of the photogrammetric technique in the low visibility of murky lagoon water with a strong current and constant tide. These conditioning factors have determined the employment of digital technologies to obtain a 3D model of archaeological sites in the Venice Lagoon. In these extreme conditions, typical of the Venice Lagoon, with water visibility around 0,5/1 m, digital techniques have permitted to obtain 3D models of submerged structures from the Roman period, thanks to a meticulous planning of the work, an extensive photogrammetric acquisition, and a strong topographic survey.

1. Introduction

Survey and documentation of underwater archaeological sites have to deal with the environment and the characteristic of different contexts. The widely employed underwater techniques, such as photogrammetry and topographic survey have to be applied, sometimes, in a difficult environment in which operations are complicated: strong currents, murky water, low temperature, high depth, time constraint, and low visibility are only some of the problems which could determine different solutions of survey and documentation. Each dive has to be meticulously planned to find the best survey solution to document the archaeological sites in every environmental and archaeological context, also in difficult conditions, postponing the analysis and the extensive study to lab-time. Digital technologies support and assist the archaeologists in the documentation of the site and some of these, such as photogrammetry, permit to speed up the time of the survey and to obtain a digital 3D model. Technological innovations have shown, in these last decade, great dynamism and fast development, and underwater archaeology has always demonstrated interest and necessity to employ these technologies, in order to compensate for the difficulties of the environment (Beltrame and Costa 2021).

Few case studies of documentation in archaeological sites at low visibility, which could be used as a comparison for the digital underwater survey, are known (Mahiddine et al., 2012; Van Damme 2015; Pacheco-Ruiz et al., 2018; Ditta and Auer 2021). The sites of large dimensions and with environmental characteristics similar to the lagoon are almost null; here the difficulties are not exclusively linked to the low visibility, but also to strong currents, which consequently determine a very tight logistics of the coordination of the survey, unlike in other contexts.

2. Survey and photogrammetry

In underwater context, the most useful and widely employed technique is the photogrammetry; since 1960–70s archaeologists have employed photogrammetry to document underwater sites, adapting the knowledge on the aerial survey and the first stereo-pairs cameras to underwater conditions (Bass, 1966; Fioravanti 1971; Hohle, 1971; Leatherdale and Turner, 1991; Capra, 1992). These stereo-pairs cameras guaranteed accuracy in recording, measuring, and interpreting photographic images, but they imposed operating constraints, such as parallel optical axes in accordance with stereo-vision conditions, and they required a high degree of technical knowledge (Fioravanti 1971; Gianfrotta and Pomey 1981, 118–124; Green 2004).

The requirement to reduce the underwater time for hyperbaric and environmental reasons, combined with the requirement to produce detailed and accurate three-dimensional mapping, has driven the researchers to improve the photogrammetric technique, focusing on a faster and more suitable technique of documentation. Image-based techniques and multi-image digital photogrammetry based on Structure from motion algorithms are now recognized as powerful, accessible, and no-destructive tools for underwater archaeological sites. It is known

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from 2000 to 2005 in terrestrial context and used in architecture and building applications, but, in the last decade, 3D surveys and photogrammetric techniques are widely used in the archaeological and cultural heritage context and the advantages of this technology were immediately evident to underwater researchers, both in archaeological excavation and biologic and naturalistic applications (Drap et al., 2007; Mc Carthy et al. 2020; Nocerino et al. 2020).

From the 60s till nowadays, indeed, the photogrammetric technique, starting from the same analytic and geometric theory, has changed the operativity and the camera employment:

- **Operativity:** the technique does not require the construction of a metal grid or other supports for the parallelism of the optical axes and the fixed overlapping of the images, but works with free shots; nevertheless, it is necessary to maintain a good regularity during the acquisition of the images, to allow a better alignment of the frames and high accuracy and metric correctness of the model (Fangi 1997; Green, 2004; Cannarozzo et al., 2012).
- **Instrument:** Multi-image photogrammetry can be performed with any underwater or suitcase camera: the metric stereo-camera used in the last century moved to a professional single camera (reflex camera and mirrorless) till the employment of amateur action camera (compact camera and GoPro) (Canciani et al., 2003; Costa et al., 2018).
- **Software:** The used modern digital photogrammetric software, both professional and open-source or open-access, allows solving mathematical algorithms in a semi-automatic way, converting photogrammetry into a quick and economical technique in replacement of a complex, expensive and long procedure. These software are less restrictive than the analogical ones, permitting to align blocks of frames with a less controlled distribution and allowing to overcome the problem of underwater distortion given by the lenses. Furthermore, these could be used on laptop and the processing of low-resolution data can be carried out directly on the excavation, in order to check the documentation and organize the survey for the next days (Green et al., 2002; Canciani et al., 2003; McCarthy and Benjamin 2014; Van Damme, 2015).
- **Results**: Multi-image photogrammetry, as a result of the alignment processing of the photogrammetric survey, creates a 3D model of a triangulated mesh built on a dense point cloud. The accuracy and the continuity of the photogrammetric model are counterposed to the few measurements and the vectorial drawing of the traditional documentation. (McCarthy and Benjamin, 2014).

The extensive use at different scales and in different sectors of expertise has permitted researchers and archaeologists to acquire more technical and practical knowledge, without the support of specialized technicians, offering a tool that is easy to use, fast and economic. The versatility of multi-image photogrammetry permits to employ this technique in many archaeological sites and different environmental conditions, such as good or bad visibility, shallow and high water (Skarlatos et al., 2012; Diamanti and Vlachaki 2015; Drap et al., 2013), and in various archaeological context, such as shipwrecks, cargos of amphoras, underwater structures, harbours and isolated (Demesticha et al., 2014; Yamafume et al., 2016). Furthermore, and most importantly, this tool brings the study and analysis to exceptional results, from the viewpoint of both scientific and disseminative outcomes.

3. The lagoon as underwater environment

The team of Ca' Foscari University has pushed photogrammetry towards new frontiers, thanks to the recent excavations organized in the lagoon and in the sea of Venice which are characterized by strong currents and murky waters.[1] The Venice lagoon represents an important case study, both for the very low visibility, from a few centimetres to one or 2 m in exceptional conditions (Fig. 1), and for the daily high tidal excursion that creates very strong currents. The characteristics of this environment have demonstrated and highlighted the importance of a digital and virtual approach for the documentation and survey.

The Venice Lagoon, the largest in the Mediterranean Sea, is a well-known example of micro-tidal environments; it stretches for almost 50 km in length and 13 km in width and it is a 550 km^2 wide shallow basin, with an average water depth (excluding the main channels) about 1.00 m. It is separated from the Adriatic Sea by two long and narrow islands-coasts and communicates with the sea through three large canals called harbour inlet, which caused tidal excursion of about 0.70 m every 6 h which can suddenly be enhanced by meteorological forcing (Carniello et al., 2012). Inside the lagoon, there are 62 islands surrounded by a dense net of channels of different dimensions and depths; the hydrodynamic pattern is connected to the tide, and it is strongly influenced by the configuration of the channels, performing a drainage function, often continuing to flow after the tide has receded. Many studies and field campaigns have shown that the Venice Lagoon is under erosion with a loss of fine sediment and the tidal currents enhance erosion and transport the suspended sediment through the inlets out to the sea (D'Alpaos and Defina, 2007; Carniello et al., 2012).

The astronomical tide can be calculated with high precision; in the Venice lagoon, it is essentially semidiurnal with two maximum and two minimum heights within 24 h; the graph 2A shows the calendar of an entire month on which are specified the water heights in centimetres from zero (the medium water level of the sea) and the corresponding time of the day for the minimum and the maximum heights of the tide. On the days of the new moon and full moon, the effects of the Sun and Moon result in the highest tidal fluctuations (Fig. 2A, second and fourth lines of the graph): during these weeks, when the tide range from min to max is impressive, the speed of the current is very high too, whereas, at first and last quarter, the tide has a smaller range, entailing a decrease in the speed of the current. This water movement is shown in graph 2B, where the speed, in cm/sec, is represented with a positive curve trend for the incoming water and conversely, a negative trend for the outcoming water. Furthermore, the tidal dynamics were also affected by the variations in morphological conditions that the lagoon has undergone over time, partly due to the natural evolutionary processes typical of lagoon environments, but largely triggered by the anthropic interventions of MOSE. A study model on the propagation and dissipation of the water in the lagoon by Matticchio et al. highlights that the variation of the geometric configuration of the mouths, and in particular the narrowing of the section, leads to an increase in the maximum speeds of the current flowing through the mouths themselves (Matticchio et al., 2017, 158–9, 174).

The San Felice channel, one of the largest and deepest of the North Venice lagoon, is highly influenced by the tide due to its proximity to the inlet (Fig. 3). This environmental condition influences the logistics of the excavation and the survey of the archaeological campaign, which are closely linked to the tide itself; often, it is impossible to operate in easy and safe conditions, especially on days of high tide. During the days of the maximum range of the tide, the currents can reach high speeds, such as to avoid stability on the seabed without safety ropes or holding the structure of the site. During some static operations, such as the excavation or cleaning phases, sometimes, it is possible to work, and, furthermore, the current could facilitate the removal of the excavated sand. Frequently, it is necessary to wait a time to avoid the maximum peak to operate safely in a less strong current (Rosso, 1987, 46–47).

In addition to the strength of the current, a not secondary aspect is

[1] The excavations and the surveys have been carried out under the direction of Carlo Beltrame, during the Interreg Italy-Croatia UnderwaterMuse project.

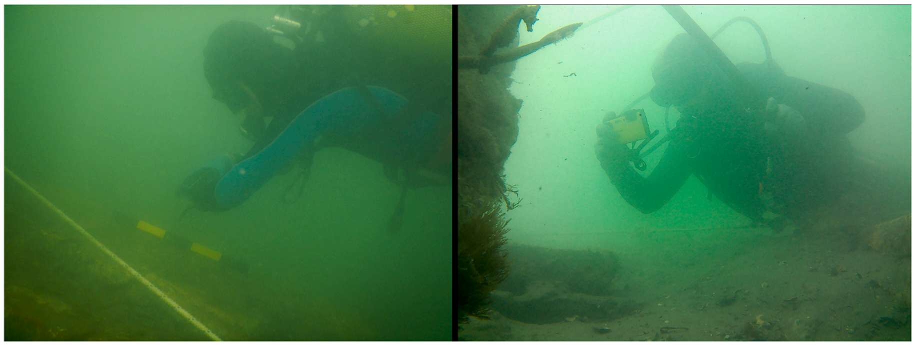

Fig. 1. Images during the photographic documentation of the San Felice archaeological site.

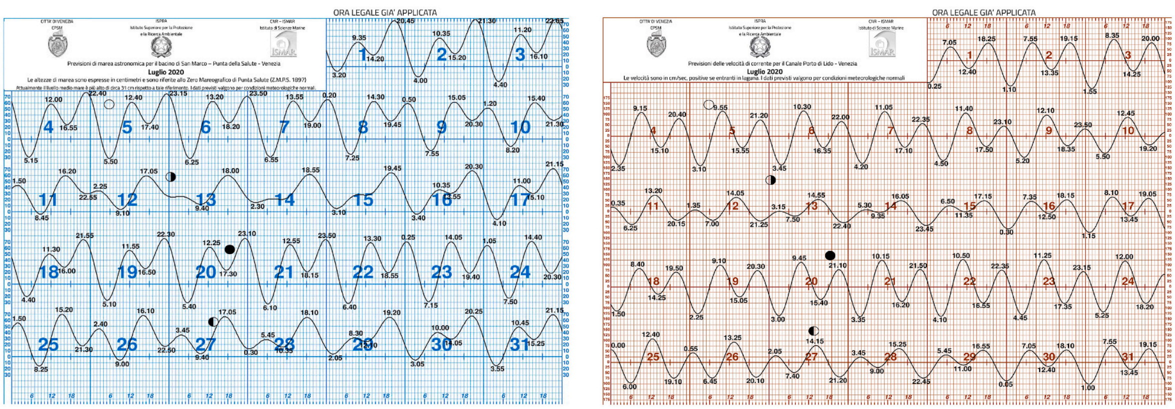

Fig. 2. A. Astronomical calendar of the tide in Venice in July. B. Astronomical calendar of the speed of the tide in Venice in July.

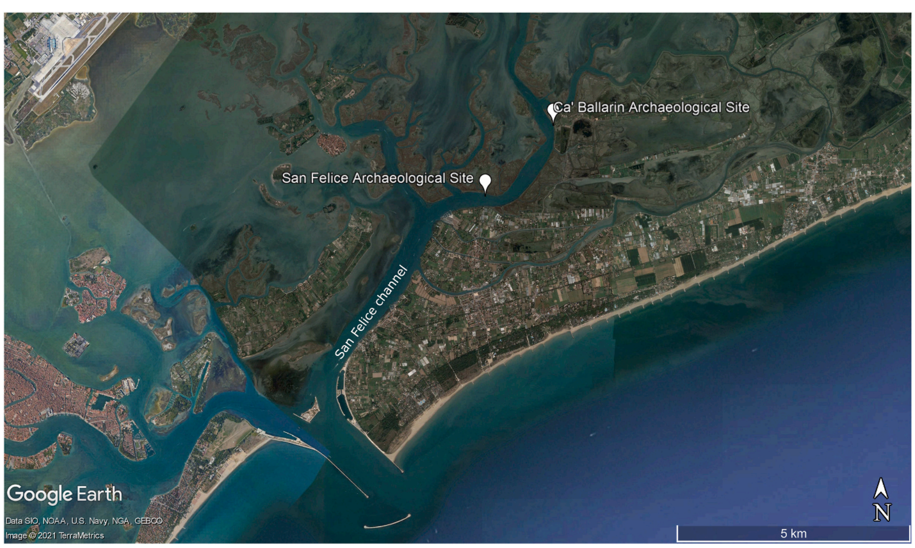

Fig. 3. Aerial images by Google Maps of the two archaeological sites.

linked to the type of tide, entering or outgoing the lagoon; during a decreasing tide, the water, going from the lagoon to the sea, washed out the islands and the lagoon bottom causing a lot of muddy suspensions, reducing visibility to a few centimetres. In this condition, excavation, cleaning, manual survey, and measurements can be carried out by expert divers, while the documentation and photographic survey phases are not feasible (Auer and Ditta 2019, 7). On the other hand, during a rising tide, with water entering from the sea towards the lagoon, the water is clearer, especially during the last phase of the rising tide and in the areas adjacent to the largest main canals and near the inlets, becoming increasingly dirty towards the extreme areas of the lagoon, where the washout of the seabed still exists. Usually, in this tidal condition, there is sufficient or good visibility around half a meter/1 m, and, consequently, photographic documentation phases are often possible.

Since working days are always influenced by this dynamic, it was necessary to divide the different operative phases in a perfect scheduled time: the time of the day of the rising tide or the moment of the changing tide is the perfect moment for the operator responsible for photographic documentation and photogrammetric survey because these are the only moments when the visibility is good or at least sufficient.

Usually, at the end of the excavation day, the photogrammetric survey should be carried out to daily document the excavation phases, but, above all, to achieve a documentation result, even if it is only a portion of a site or a roughly cleaned site. The ongoing documentation is useful for at least two reasons: to create a partial plan of the site as a reference on which the team could discuss the future procedures on the site and the new position of the excavation on the following days of work and to obtain a photogrammetric model as documentation in cases of force majeure, such as worse visibility, the collapse of the structure or the interruption of the excavation.

4. The survey in the lagoon

The whole lagoon and its islands retain traces of human settlements from Prehistory. The number of known archaeological sites in the lagoon area, most of which have now disappeared underwater due to subsidence and eustatism, can be estimated at around 300, going to consider the Venice Lagoon as the largest submerged archaeological area in the world. The typology of archaeological sites is very different, but they are mainly linked to settlement and employment of the lagoon territory, including well-documented embankment structures for the Antiquity and the Early Medieval Ages. The investigations of part of these underwater archaeological sites have permitted us to determine the characterization of the landscape of the ancient lagoon with scattered settlements that took advantage of environmental resources thanks to providing systems for the management of water and land (Canal, 2010).

Until now, the surveys in the lagoon in low visibility context were made through direct measurement as trilateration of the points for a bidimensional plan, through the construction of a grid on the site and manual survey, sometimes the use of a total station, while, from the photographic point of view, low visibility were sometimes solved through an instrument called clear water cone, a trapezoidal viewer realized in transparent plexiglass filled with clear water which allows a better view of the seabed and the findings (Arnold 1973; Rosso, 1987, 243–248; Bowens 2009).

The case studies of the UnderwaterMuse project included several archaeological sites (5 sites in the lagoon, 3 sites in the sea) and the excavations and the survey of these sites had to carefully follow the marine weather conditions and the dynamics of tides previously described; furthermore, the schedule was different according to the survey areas, the type of environmental context, the type of archaeological site, and the type of documentation that was necessary to produce. Consequently, the schedule of the excavations and surveys is based on finding the best underwater conditions for every site.

Two of these archaeological sites in the lagoon proved to be interesting both from the historical and technical point of view and especially for the documentation and survey technique: the Roman so-called “tower”, a large *sesquipedali* brick structure, laying in the San Felice channel and the Roman pier at Ca’ Ballarin, fragmented into 7 elements; these sites have been already known by researchers (D’Agostino and Medas 2010; Canal 2010; D’Agostino et al., 2020), but they have been documented only with direct manual measurement, drawings, and some images. The survey and documentation that will be illustrated concern these sites on which the environmental conditions are the most arduous to produce good documentation and photogrammetric result.

4.1. Operativity

First of all, the photographic documentation has to be organized following the schedule of the tide as previously described. The photogrammetric survey has been realized inspecting the environmental conditions and waiting for two different favourable moments: at the end of the rising tide when the suspensions are minimal because the water has finished to bring with it the sediments of the muddy lagoon bottom and during the inversion of the tide, when the strength of the current begins to reduce, till to reach a moment of calm water before changing direction.

Despite this expedient, it was not possible to record the site all the days because the visibility was not sufficient neither during the rising tide or the strength of the tide was too high. Differently from the excavation phase, where the divers could stay on the bottom, during the photogrammetric survey phase, the diver has to swim over the bottom, in the middle of the current.

In the underwater survey, the most suitable photogrammetric scheme is represented by the union of nadiral strips, orthogonal to the subject, made swimming over the sites maintaining the correct overlap between the strips, and by radial strips at different degrees around the subject to document the lateral portion, according to a well-known arrangement used in various contexts (Balletti et al., 2016; Beltrame and Costa, 2017; Auer and Ditta, 2019).

We have followed this procedure also in this difficult underwater context. The diver has to move regularly to allow the alignment of the images and obtain a correct photogrammetric survey, following parallel and overlapping strips with alternates directions between lines; this is called a serpentine or boustrophedon movement. In conditions of high tide, the difficulty of maintaining the correct movement could invalidate the survey and several tests have been carried out before adopting the correct technique. On the San Felice site, only two days of mild current made it possible to carry out the strips with a lateral current to maintain a constant speed for both gaits and without moving the orientation of the camera, simplifying the alignment of the images, while the other days the strips were made always swimming against the current and, consequently, without a boustrophedon survey but only in one direction.

Based on visibility and tide, the operating time was never greater than half an hour and therefore it was not possible to survey the site of San Felice in its complexity, but only for portions of various sizes depending on the tide and visibility of the day. The days of the survey can be clearly visible from the orthophoto plan in Fig. 6A where the different colours of the model reflect the different photogrammetric surveys.

The surveys have been combined to obtain the complete model of the archaeological site thanks to 20 targets regularly placed on the structures; the known coordinates of them have been obtained from a topographic survey performed with two techniques. Firstly, through trilateration computed as a 3D topographic network using rigorous Least Squares techniques, following the DSM (Direct Survey Method) technique (Rule, 1989; Bowens, ed., 2009, 127–132); the data were processed with Site Recorder software to create x, y, z coordinate of the targets in a relative local system. Secondly, the topographic survey has been performed with a total station to achieved further control and accuracy (Fig. 4) and this technique has been possible in this underwater situation due to the low depth and the vicinity to the shore (Mitchell

Fig. 4. The total station positioned on the land near the archaeological site for the topographic survey.

1983; Rosso 1987; Bowens, ed., 2009: 133–134; Balletti et al., 2016; Abdelaziz and Elsayed, 2019).

The depth of the artifact is from 2.5 m to 4 m; therefore, a sufficiently long pole with a prism on the top was built. To ensure that this pole remained automatically vertical, a large weight was applied to the base and a large polystyrene float on the top. In this way, the pole just positioned on the point remained still and vertical, and, furthermore, the presence of a spirit level improved the maintenance of verticality (Fig. 5). Both these techniques have presented some problems during their realization: for the trilateration survey, the communication between the two operators was difficult due to the low visibility and it was difficult to check the straightness of the measuring tape; for the total station survey, the verticality of the long pole, so easily reachable in terrestrial surveys, was difficult to maintain due to the length itself and the water current. For this reason, the analytical comparison between the coordinates obtained with the two different techniques was not carried out.

This technique, despite the problematics, allows to orient the wreck not only in a local reference system to combine the different surveys and create a single model but allows to accurately georeference the archaeological site in a global reference system.

The survey of the Ca' Ballarin archaeological site did not have the same critical aspects as at the San Felice channel, due to the different disposition of the structures and due to the position of the sites more protected from the tides. The structure is a Roman pier broken into 7 blocks, which were surveyed individually due to the distance from each other and the small size of the items (1.5–6 m length x 0.6–0.8 m width x 0.45 m height); every block has been documented, in around 15 min, with three nadiral strips on the upper part and two radial strips around the vertical surfaces, managing to complete the survey in a single immersion of 1 h and a half.

On the Ca' Ballarin site, every single block was provided with 3 measured targets to accurately scale and correctly arrange every item on the bottom. The 3D coordinates of these targets, obtained through a trilaterated net with DSM (Direct Survey Method), permits the blocks to be inserted into the same local reference system; then, it has been checked and adjusted on a previous excavation plan realized through a geo-referenced topographic survey system during the first excavation project, conducted by Consorzio Venezia Nuova company in 1998–2002 (D'Agostino et al., 2020).

In every excavation and survey, we always paid particular attention to the topographical aspect in order to scale, place in a reference system, and metrically check the models even if the survey is carried out in a single dive, as usually occurs in less complex contexts (Yamafune et al., 2016; Beltrame and Costa 2017; Ditta and Auer 2021).

Fig. 5. The long pole with the prism employed for the topographic survey.

4.2. Instrument

Usually, the best camera employed for a survey is a professional reflex camera, with a full-frame sensor and a fixed 20 mm lens, but in a difficult underwater environment conditioned by a strong current, the use of a camera reflex with an underwater housing and a hemispheric dome has proved to be difficult even in the best conditions, due to its size and its resistance to current; the use of a small compact camera allows us to counteract the current to a minimum or to keep one hand free for "anchoring" ourselves to a safety rope and easily swim to realize the survey. Furthermore, this difficult working condition did not allow a sufficient static position to shoot still photographs and it was decided to use a video recording for the photogrammetric survey; this allowed to swim more freely but regularly and, given the limited field vision, permit to extrapolate frames every second obtaining a high number of images with a good overlap.

The images and videos have been realized with a Nikon Coolpix W300 compact camera, with a focal length of 24 mm, with video in 4K, and an image size of 4608 × 3456 pixels. The possibility of a pre-calibration of the white balance has allowed obtaining videos with better colours and the excellent quality of the lenses and the aperture of 2.8 f permit to obtain high-quality videos and brighter and less noisy images even in conditions of low visibility, where the light is poor and the suspension is higher.

4.3. Software

Image enhancement technique, based on qualitative criteria such as contrast and histogram matching, is an approach to overcome the problematics of the correct and realistic colour imagery of underwater sites very employed in the last decade in different fields of research (Hitam et al., 2013; Ghani and Isa, 2014; Agrafiotis et al., 2017). Enhancement processes of colour correction, sharpening, brightness, and contrast have been performed directly on the videos through DaVinci Resolve software. The radiometry of the different videos used for the reconstruction of the archaeological site model was not completely homogeneous due to the different underwater visibility on the days of the survey which caused different filtering of light on the subject (Fig. 6A).

Then, the frames were extrapolated every second, a sufficient time framing to achieve sharp images and also a good overlap between the frames as the underwater operator maintained a low and constant speed during the video shooting. The frames were used for photogrammetric elaboration through Agisoft Metashape software, aligning the images and creating a dense point cloud. Data processing took place daily at the end of the survey operations, during the evening once the day in the field was over, in order to check the actual success of the survey and to understand if the following days it was necessary to redo the survey in the same portion of the site or it is possible to proceed with other areas. Given the high number of frames, data processing was carried out in the first place at a low quality, both for the alignment of the images and for the dense point cloud, to be able to process a model in few hours, before the next day. Low-quality elaboration allows obtaining a 3D model, which is useful for a preliminary check and also as a preliminary excavation plan useful for the excavation, survey, or recovery of finds (Auer and Ditta, 2019, p. 10; Ditta and Auer, 2021).

Finally, the definitive documentation has been processed from seven videos on the San Felice and eight on the Ca' Ballarin site; each model obtained was georeferenced through the coordinates from the topographic survey by the total station and DSM survey. The coordinates were inserted in Agisoft Metashape, in correspondence to the targets and they were employed both to roto-translate the models in the right position and to check the position of the targets to evaluate the final accuracy.

Previous studies (Costa et al., 2018) have shown how the photogrammetric model obtained from the video frames, compared with one

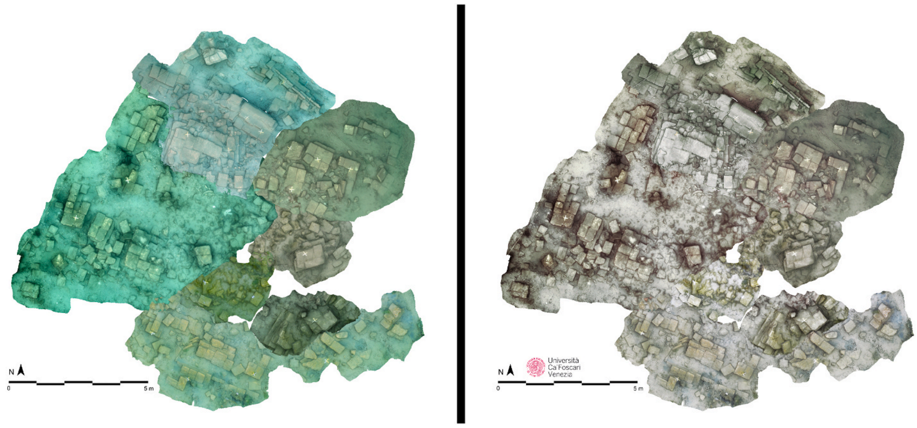

Fig. 6. Orthophotos from the photogrammetric survey of the San Felice archaeological site. A. Orthophoto with the original colours from the videos; B. Orthophoto with modified colours in post-processing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

from the images of the same camera (a GoPro Hero 5), presents a radial deformation around 2 cm, probably due to the lack of known Exif data of the video frames, including the focal length of the image. The models resulting from the photogrammetric survey on the San Felice site show the same deformation, which has been compensated through the optimization parameters of the software's automatic Camera Calibration Tool. In addition, by importing the separate 3D models and coordinates into the Rhino software, it was possible to further adjust the model by eliminating its remaining curvature with the measured coordinates of the targets.

The same modelling software has been used to hypothesize a reconstruction of the complete Roman pier of Ca' Ballarin, with an original dimension of about 18 m in length, 80 cm in width, and from 40 to 60 cm in thickness (Fig. 10). The seven portions of the pier have been rotated and arranged on the supposed correct position and the wooden poles, stuck into the bottom under a little portion of the pier, have been added in a regular position as a support of the structure also below the other items which have lost this kind of reinforcement during the century (Fontaine et al., 2021, 185–187).

4.4. Results

For the definitive studies, analysis, and publication of the San Felice archaeological site, various high-resolution two-dimensional output formats were generated from the three-dimensional model:

- a complete orthophoto, with a resolution of 1 mm/pixel employed for a 1:5 nominal scale, on which it could be recognized the different videos colour of the surveys on different days (Fig. 6A).
- a complete orthophoto, with a resolution of 1 mm/pixel employed for a 1:5 nominal scale, with a final post-production radiometric enhancement (Fig. 6B).
- a DEM (digital elevation model) from the photogrammetric model, with a colour range from −4.24 m of maximum depth (blue) to −2.53 m of minimum depth (red), with bathymetric curves every 5 cm (Fig. 7).
- the orthophoto and the point cloud from MultiBeam survey realized during the campaign by Elmar Marin Survey s.r.l. overlapped to a Google Maps (Fig. 8).

For the definitive studies, analysis and publication of Ca' Ballarin archaeological site, various high-resolution two-dimensional output formats and elaboration of the three-dimensional model:

- a complete orthophoto, with a resolution of 2 mm/pixel employed for a 1:10 nominal scale (Fig. 9).

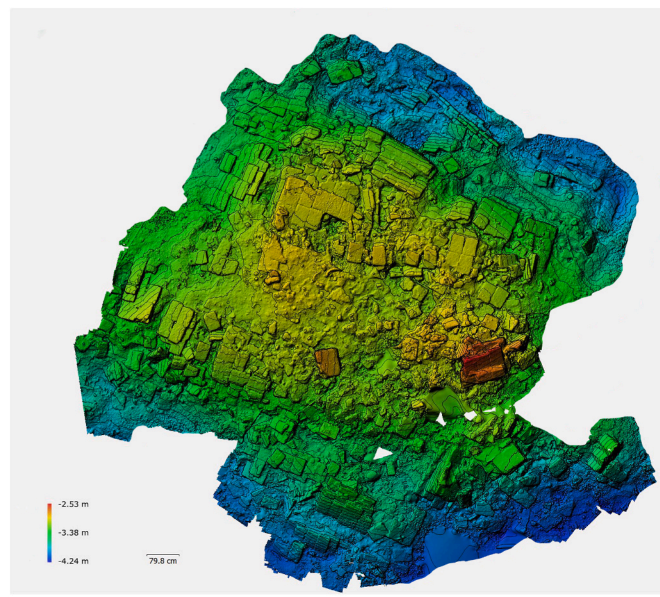

Fig. 7. DEM (digital elevation model) from the photogrammetric model, with a colour range from −4.24 m of maximum depth (blue) to −2.53 m of minimum depth (red), with bathymetric curves every 5 cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

- A hypothetical reconstruction of the original pier (Fig. 10).

5. Conclusions

The survey of the largest sites, San Felice, over an area of 150 m^2, has required a long and difficult post-processing phase of the data acquired, but the 3D model and the orthophotos obtained have reached a good metric accuracy and a high resolution of photographic texture. This site, documented in different campaigns (from the '80s to 2000) with manual drawings and images, only in 2020 has been documented with photogrammetric technique, obtaining probably the finest survey ever produced in the Venice lagoon context. In this situation, digital technologies have permitted us to overcome the difficulties of the manual survey and direct measurement, which can cause various errors due to a documentation of small portions in different moments. The survey of the pier in Ca' Ballarin, with its fragments scattered over an area of about 10 × 25 m, has given the possibility to enhance the quality and the results in comparison with the surveys conducted in the last two decades.

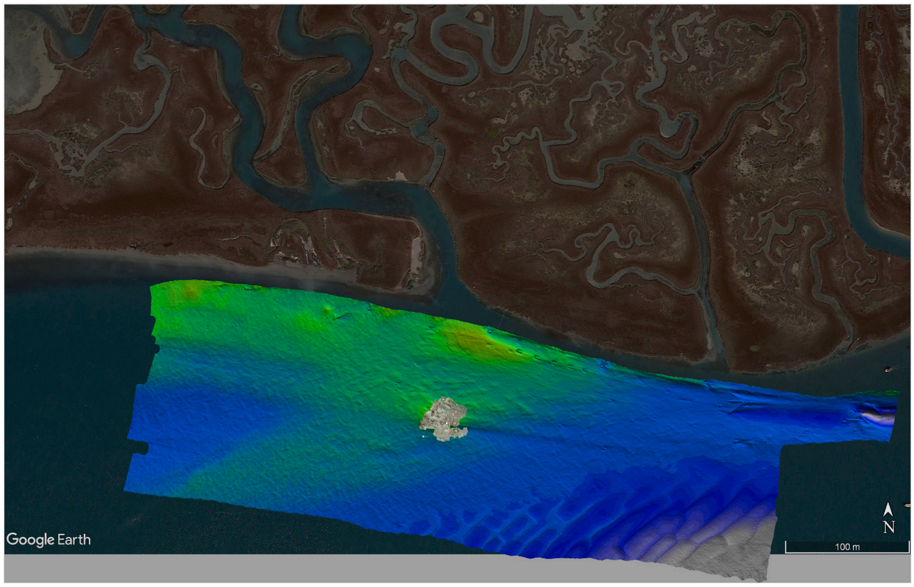

Fig. 8. Orthophoto and the point cloud from MultiBeam survey realized during the campaign by Elmar Marin Survey s.r.l. overlapped to Google Maps.

Fig. 9. Orthophoto from the photogrammetric survey of the Ca' Ballarin archaeological site.

Fig. 10. Reconstruction of the hypothetical Roman pier of Ca' Ballarin.

Three-dimensional surveying techniques can become an essential tool also for archaeology in the lagoon: portability, low cost, fast acquisition, and, at the same time, accuracy and high quality of the photogrammetry allows it to be used in situations where other technology would be inappropriate. The 3D surveys have outdone the slower 2D surveys subjected to the interpretation of the surveyor; 3D virtual models have been used to solve the problem of the 2D documentation, which does not allow a clear comprehension of the volume of the sites. The development of the survey techniques of the last decade has brought the documentation to a new approach and a new life of the archaeological site and digital techniques are essential to recreate an accurate virtual model which could ensure reliable visualization outputs.

In these contexts and with water visibility around 0,5/1 m, also digital techniques are arduous to use, and only meticulous planning of the work inspecting the environmental conditions, an extensive photogrammetric acquisition, and a strong topographic survey permit to obtain good results on wide archaeological site otherwise invisible in its entirety. In fact, one of the most important aspects of this experience is the relevance of the topographical aspect used as a fundamental for the 3D photogrammetric survey; the determination of a unique reference system for all the portions of the site surveyed has given the possibility to accurately obtain a complete model of the whole site.

This experience has confirmed how the digital approach, despite the difficulties of the lagoon environment, offers the precious opportunity to produce an entire overview of a wide underwater archaeological site, which implies an enormous advantage for its understanding and appreciation, in particular in a lagoon context where a site is not completely visible simultaneously. This exclusive environment can finally be accessible to everyone in a virtual and digital mode, sharing an underwater cultural heritage with researchers and the public.

Author statement

Elisa Costa: Conceptualization; Data curation; Formal analysis;

Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/ Writing - original draft; Writing - review & editing.

Declaration of competing interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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