

EXPLORING THE UNESCO WORLD HERITAGE PROPERTY IN THE SHALLOW WATERS AT ROSE ISLAND USING UNMANNED SURFACE VEHICLES (USV)

STEFAN PLATTNER^(*) & MARKUS GSCHWIND^(**)

^(*)German Aerospace Center (DLR) - Remote Sensing Technology Institute, Oberpfaffenhofen - Wessling, Germany

^(**)Bavarian State Office for Monument Protection - Weißenburg i. Bay, Germany

Corresponding author: stefan.plattner@dlr.de

EXTENDED ABSTRACT

Le acque poco profonde intorno all'Isola delle Rose, nel Lago di Starnberg in Germania, fanno parte del sito Patrimonio dell'Umanità dell'UNESCO "Abitazioni palafitticole preistoriche attorno alle Alpi". Nell'ambito del progetto TRIQUERTA, finanziato dal programma di ricerca e innovazione dell'UE "Horizon Europe" (GA No. 101094818), è uno degli otto siti pilota per lo studio dei rischi del cambiamento climatico sul patrimonio culturale. I resti archeologici di quest'area risalgono fino al Medio Neolitico, con i periodi di massimo sviluppo dell'attività di insediamento preistorico durante due fasi dell'Età del Bronzo. Inoltre, gli ultimi resti noti di palafitte attorno alle Alpi provengono proprio dall'Isola delle Rose. Poiché mancava una mappa batimetrica sufficientemente affidabile e dettagliata delle acque intorno all'isola, e in cerca di un approccio efficace per documentare la posizione, l'estensione e lo stato delle ampie strutture in legno presenti sul fondale lacustre, nel 2023 e nel 2024 sono state condotte rispettivamente una campagna sonar e una campagna fotogrammetrica dal Centro Aerospaziale Tedesco (DLR).

Durante la campagna del 2023, i dati sonar lungo transetti con una distanza tra le linee di 10 m e una lunghezza totale di 60 km sono stati raccolti da un veicolo di superficie senza equipaggio (USV) e trasformati in una mappa batimetrica dettagliata del sito Patrimonio dell'Umanità dell'UNESCO, comprese le sue zone cuscinetto adiacenti. Questa mappa rappresenta una risorsa inestimabile per ogni ulteriore lavoro di esplorazione e protezione del sito e costituisce un importante set di geodati per il sistema di supporto alle decisioni (DSS) e il WebGIS che saranno implementati nell'ambito di TRIQUERTA. Durante una campagna fotogrammetrica nell'estate del 2024, utilizzando una telecamera montata sulla piattaforma multi-strumento senza equipaggio LimnoVIS del DLR, sono state raccolte circa 15.000 immagini verticali ad alta risoluzione e precisamente localizzate del fondale lacustre vicino alla punta nord-est dell'Isola delle Rose.

Quest'area contiene una densità elevata di travi che sono esposte all'acqua in una zona molto poco profonda, essendo una delle parti più interessanti ma anche più vulnerabili del patrimonio culturale. Dalle immagini, scattate da una posizione della telecamera appena sotto la superficie dell'acqua, sono stati generati modelli 3D ad alta risoluzione e texture del fondale lacustre e dei resti in legno, utilizzando il metodo *structure-from-motion* (SfM) per un'area di circa 1150 m².

Questi modelli forniscono informazioni precise sulla posizione, le dimensioni e lo stato attuale dei reperti archeologici sul fondale lacustre e possono essere utilizzati per studiare approfonditamente i resti che altrimenti sarebbero accessibili solo ai subacquei. Le campagne ripetute potrebbero rivelare i tassi di erosione e accumulo dei sedimenti e il processo di degradazione dei reperti nel tempo, supportando così lo sviluppo di misure di mitigazione e il processo decisionale riguardante la protezione del patrimonio culturale. Inoltre, i modelli offrono un eccellente strumento per la visualizzazione 3D, rendendo il patrimonio culturale tangibile per un pubblico più ampio.

ABSTRACT

Rose Island (Germany) is part of the UNESCO World Heritage site “Prehistoric Pile Dwellings around the Alps” and a pilot site of the EU funded project TRIQUETRA, which targets the risks of climate change on cultural heritage. With the lack of a detailed bathymetric map of the waters around Rose Island and in search for an efficient approach for documenting the wooden relics from Iron Age at the lake bottom, both a sonar and a photogrammetric campaign were conducted by the German Aerospace Center (DLR). From the sonar measurements, the first reliable bathymetric map of the area was generated and provided to TRIQUETRA’s decision support system and WebGIS. During the photogrammetric survey, ~15.000 high resolution images of the lake floor were taken by an unmanned surface vehicle (USV) and processed to high-resolution 3D models by using the structure-from-motion method (SfM). The models provide an unprecedented level of detail for the documentation and examination of the archaeological remains at Rose Island and a fascinating insight to the prehistoric settlement remains for the general public.

KEYWORDS: underwater; photogrammetry; archaeology; cultural heritage; pile dwellings; erosion; USV; 3D imaging; sonar; SfM.

INTRODUCTION

Roseninsel (Rose Island) is the only island in Lake Starnberg which is situated south-west of Munich (Germany) and is surrounded by a large shallow water zone (see Fig. 1). The island’s special topographic location and probably also the resources of fish and water birds attracted the attention of people early on.



Fig. 1 - Overview of the UNESCO World Heritage property (green) and buffer zone (blue) at the western shore of Lake Starnberg (Germany). Erosion markers cover mainly the core zone and are shown in orange. Background: Aerial image by DLR

The earliest piece of evidence for human presence at Rose Island is a single fragment of middle Neolithic pottery that was found in a summer with extreme low water and dates back to the first half of the 5th millennium BC (FESQ-MARTIN *et alii*, 2019). Further pottery finds from the Münchshöfen Culture (4.300-3.900 BC) and the Altheim culture period (3800-3400/3300 BC) indicate the existence of a permanent settlement on the island during these Late Neolithic periods.

Numerous archaeological finds show that the Bronze Age was a heyday of prehistoric settlement activity at Rose Island. The 17th/16th century BC, *i.e.* the transition period from the Early to Middle Bronze Age, and the middle to late Urnfield culture (11th - 9th century BC), *i.e.* the final phase of the Bronze Age, are particularly well represented in the archaeological finds from Rose Island and the shallow waters around it (VON SCHAB, 1876; SCHLITZER, 2023). Thus, the archaeological finds correspond quite well with Bronze Age settlement sequences of other lake shore settlements around the Alps. In contrast to that, Iron Age foundation beams situated next to the northeastern tip of the island are very peculiar, as – dating to the Early Celtic period – they provide the latest evidence of pile dwellings around the Alps at all.

In the early 8th century AD an extensive revetment of the shoreline was installed (FIEDERLING *et alii*, 2023) and from the Middle Ages until the Thirty Years’ War, the island was a pilgrimage destination (AHL & PÄFFGEN, 2023). In the 19th century it finally was transformed into a summer retreat of the Bavarian kings.

When during the second half of the 19th century, a veritable “pile dwelling fever” was rampant in Central Europe, Rose Island was the first and only pile dwelling site to be discovered and researched in Bavaria during the 19th century (VON SCHAB, 1876; PÄFFGEN & SCHLITZER, 2023).

When Rose Island became one of 111 sites in six countries that together form the transnational serial UNESCO World Heritage Site “Prehistoric Pile Dwellings around the Alps”, a site management was installed and a monitoring system set up, because a comparison of aerial photographs from different decades showed erosion in parts of the shallow water zone around the island (GSCHWIND, 2023).

In 2014, on behalf of the Bavarian State Office for Monument Protection (BLFD), the Bavarian Society for Underwater Archeology (BGfU) installed 174 wooden erosion markers in a 25×25 m grid, mostly lying within the World Heritage property (see Fig. 1). The markers’ positions (latitude, longitude, altitude) were measured and documented by using RTK GNSS (BGfU, 2014).

The height of the sediment relative to the top of this markers is measured and documented by divers of the BGfU once per year, resulting in a yearly report to BLFD. These reports contain marker-by-marker statistics as well as heatmaps showing the areas where erosion or accumulation dominate. Erosion/accumulation rates typically lie in a range of a few centimeters with a maximum

erosion of 14 cm and a maximum accumulation of 7 cm since the beginning of the monitoring in 2014. (BGfU, 2023).

However, this kind of erosion monitoring is a time-consuming, labor-intensive and therefore expensive task. Furthermore, the number of erosion markers which can't be located or properly read increases, mostly because they often get covered by macrophytes, which leads to substantial gaps in the dataset. In 2023, only 104 of total 174 erosion markers could be read (BGfU, 2023).

Apart from the known positions and depths of these erosion markers, although Rose Island is located in otherwise well-known waters, bathymetric details showing the topography of the quite uneven underwater terrain around the island are not publicly available.

In addition to erosion monitoring, BGfU also carries out the documentation of the number, position, type and condition of archeological structures visible at the bottom of the shallow waters around Rose Island. Due to the sheer size of the area and the great effort involved in deploying research divers, this had to be limited to targeted areas to solve research questions and provide additional information for a better understanding of the site and its protection.

The overall goal of all the described onsite monitoring and documentation activities carried out within the framework of World Heritage monitoring is a better understanding of the processes that threaten Rose Island as an archaeological Cultural Heritage site, because this is a precondition for developing customized protective measures and mitigation strategies for the site. Therefore BLFD included Rose Island as a Pilot Site into the National research project SuBoLakes (Sustainable Boating on Lakes in Germany; www.subolakes.de) funded by the German Federal Environmental Foundation, and the international research project TRIQUETRA (Toolbox for assessing and mitigating Climate Change risks and natural hazards threatening cultural heritage; www.triquetra-project.eu) funded from the EU HE research and innovation programme under GA No. 101094818 (GCHWIND *et alii*, 2024).

SuBoLakes analyzed the effects of passenger and leisure shipping on the shallow water areas by taking measurements at various water depths next to the Iron Age foundation beams north east of the island and developed recommendations for action. In contrast to that the EU project TRIQUETRA focusses on the impact of climate change on cultural Heritage sites in the Mediterranean and in Central Europe. 21 organizations from seven countries form the consortium of the project with Universities, Research Organizations, Cultural Heritage Authorities and private companies being represented. Together they target eight pilot sites in six countries with detailed interdisciplinary research. Two of the pilot sites are part of the UNESCO World Heritage Site "Prehistoric Pile Dwellings around the Alps". The main goal of the TRIQUETRA project is to identify, quantify and minimize the risks of climate change for cultural heritage sites and to

develop a toolbox for a risk assessment and the development of mitigation strategies for other Cultural Heritage sites.

In the scope of TRIQUETRA, both the lack of a sufficiently reliable and detailed bathymetric map of the waters around Rose island as well as the search for an approach to make the detection, the measurement and the monitoring of the condition of the wooden remnants at the lake floor more efficient and, if possible, more precise, led to two campaigns conducted by the German Aerospace Center (DLR).

DATA AND METHODS

Sonar based bathymetric survey

A first campaign took place at Rose Island on totally eight days in July and August 2023 and was a sonar survey to gather sufficient and up-to-date depth information in order to being able to generate an accurate bathymetric map as a fundamental geodata set for the use in TRIQUETRA's Decision Support System (DSS) and for the visualization in the project's WebGIS.

To gather the depth data for the production of a bathymetric map, DLR used its ultra-compact (54 cm in length), remotely controlled or autonomously operating sonar boat "La Plancha" (Fig. 2). It is equipped with a Blue Robotics Ping single-beam sonar (115 kHz), RTK GNSS and 868 MHz long range communication for remote control and telemetry. Cruising speed when conducting bathymetric measurements is typically 0.8 m/s, which gives one measurement every 8 cm along-track at a sampling rate of 10 Hz. The boat is capable of operating up to 4 hours with a full charge of its 11.1 V Lithium batteries.



Fig. 2 - The ultra-compact bathymetric survey vehicle "La Plancha" of DLR

Both the UNESCO world heritage property and its buffer zone were surveyed by taking sonar measurements along east-west transects with a track-to-track distance of 10 m and a total pathlength of ~60 km (Fig. 3). When navigating on these tracks, the boat operated fully autonomously.

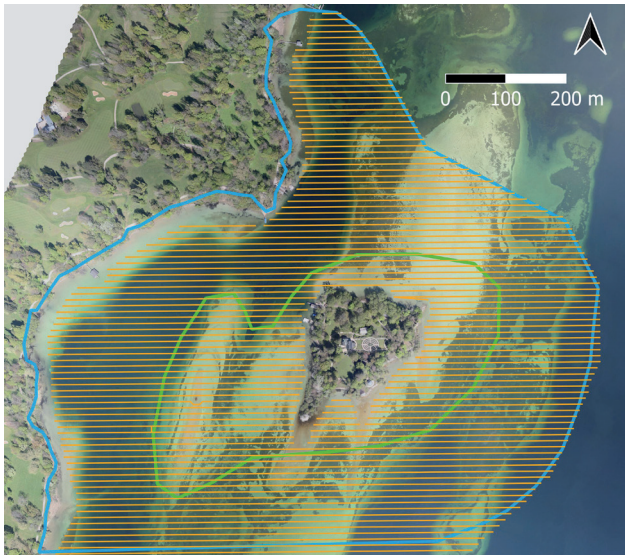


Fig. 3 - The bathymetric survey covered both the World Heritage property (green) and its buffer zone (blue). Around 60 km of survey tracks (orange) were recorded autonomously. Only areas close to the shore were recorded by steering the USV manually. Background: Aerial image by DLR

Only very shallow areas close to the shore of Rose Island and in the vicinity of the mainland had to be surveyed by controlling the vehicle manually, thus avoiding collisions with the shoreline, the ground or riparian vegetation.

Since the campaign took place on multiple days, the relative day-to-day changes of the water level had to be monitored during the whole timespan in order to being able to correct the data for the varying height of the water surface later. This was done by using a pole on a jetty where the distance from its top to the water surface was measured.

In order to reduce the large amount of depth data in a long-track direction, an average over 5 measurements was applied, resulting in a data point every 40 cm. These datapoints were visualized with the bathymetry software ReefMaster and outliers were removed manually.

All depth values were corrected for the vertical distance between the water surface and the transducer of the sonar (4 cm) as well as for the daily fluctuations of the water level. As a reference value, the water level of the first day of the survey (583.9 m above sea level, measured using RTK GNSS near Rose Island) was used. All depth information in the derived bathymetric map refer to this level.

Photogrammetric survey of pile dwelling remains

The second campaign at Rose Island was conducted on multiple days in May, June and July 2024 and was a photogrammetric survey to gather high-resolution images of the lake bottom near the north eastern tip of the island, where a high density of timbers exposed to the water can be found. The goal of the second campaign was to find if automatically gathered, close-range, high-resolutions images can be used to gain better information about the position, type, size and condition of the wooden relics or if it is possible to obtain this kind of information more efficiently than it can be done by divers.

Photogrammetric techniques have been used for about sixty years in underwater archaeology (DRAP, 2012), with a big increase in popularity with the advent of easy to use software tools based on the Structure-from-Motion (SfM) technique like Agisoft Metashape, Pix4DMapper or OpenDroneMap. Usually, images used for creating 3D models using such tools are taken by divers or by remotely operated underwater vehicles (ROVs).

The fact that large parts of the archaeological remains at Rose Island lie at depths around 0.5 - 3 m, in conjunction with the clear waters of Lake Starnberg, allows for the use of a USV equipped with a camera mounted just below the water surface for this task. Such a vehicle can scan the bottom of the shallow water in a line-by-line survey pattern similar to the process how an aerial drone collects photos for a digital elevation model (DEM). Similar work was done by HATCHER *et alii* (2020), by using a platform equipped with five synchronized cameras, towed by a manned boat for the photogrammetric mapping of coral reefs in Florida.

The unmanned surface vehicle (USV) LimnoVIS (130 cm in length) was developed at DLR as a multi-instrument platform for the autonomous or remotely controlled collection of in-situ data used for the validation of optical satellite data and processing algorithms (PLATTNER *et alii*, 2023). For the purpose of collecting images during the TRIQUETRA photogrammetric survey, it was equipped with a sub-surface, down-looking camera (Fig. 4).

The camera system consists of a USB computer vision camera based on the Sony IMX 264 global shutter 5 MP sensor with an RGB Bayer array and a Fujinon HF6XA-5M fixed focus 6 mm wide angle lens. It is installed in a watertight enclosure covered by a hemispherical dome port and provides a horizontal field of view (FOV) of 70°. Both camera and lens are mounted on a longitudinal aluminum rail so that the nodal point of the lens can be aligned with the center of the hemispheric dome port in order to minimize distortions due to refraction at the water/air interface (SHE, 2019).

The global shutter provides for minimal image distortions caused by the movement of the vehicle during exposure. The camera can be triggered manually via the remote control or automatically via the onboard flight controller of LimnoVIS which also records the RTK GNSS position at the exact moment when the shutter opens. Images are saved on an SSD connected



Fig. 4 - USV LimnoVIS of DLR, equipped with downward facing underwater camera in a watertight housing

to an embedded Linux computer, which also connects the camera systems to the LimnoVIS onboard LAN and provides an image server which can be accessed over a wireless connection for quality control by the operator during operation.

For the survey, an area of $\sim 1150 \text{ m}^2$ close to the northeastern tip of Rose Island was selected (Fig. 5), showing a high density of structural remains of prehistoric pile dwellings.



Fig. 5 - Area of the photogrammetric survey with LimnoVIS at the northeastern tip of Rose Island. Background: Aerial image by DLR

Since it was planned to use the SfM software Agisoft Metashape for the creation of the 3D model, images were taken with an overlap of 80 % along-track and 60 % across-track according to the recommendations in the software manual. For this task, the vehicle had to operate autonomously and with high

precision on transects with a track-to-track distance of 30 cm, which resulted from the prevailing water depth of 1 m at the time of the campaign, the desired overlap of 60 % across-track and the camera's FOV of 70° . The required precision could be achieved by using RTK GNSS with a virtual base station provided by the Bavarian SAPOS-HEPS correction service via the mobile data network, ensuring a nominal location accuracy of $\sim 1 \text{ cm}$. At a cruising speed of 0.5 m/s, the along-track overlap of 80 % could be achieved by taking one photo every 400 ms. The images were recorded on cloudy days in order to prevent disturbing caustics which are caused by the direct sunlight refracted by the waves at the water surface. In order to prevent motion blurring, a maximum exposure time of 5 ms ($1/200 \text{ s}$) was used.

In this way approx. 15.000 close-distance, overlapping vertical images were collected in the area depicted in Fig. 5.

In order to get better visualization results, the images were preprocessed prior to the application of the SfM technique. The preprocessing was done with the open source software GIMP and its Batch Image Manipulation Plugin, where an automatic histogram stretching and a mild increase of brightness and saturation were applied. Figure 6 shows a comparison between an unprocessed, raw image as recorded by the camera and the same image after it has been preprocessed.

With the images prepared this way, they were imported to Agisoft Metashape (Version 2.1.1) (AGISOFT, 2024). For generating 3D models with good precision, it is crucial to provide as much geometrical information together with the images as possible,



Fig. 6 - Comparison of raw (top) and preprocessed (bottom) underwater images from LimnoVIS camera. The images show a detail of the Celtic pile dwelling remnants near Rose Island

where the most important is the exact location where each image was recorded. In using LimnoVIS as the operating platform, it was possible to associate the RTK GNSS position (nominal accuracy 1 cm horizontally, 2-3 cm vertically) as well as pitch, roll and tilt of the vehicle (and therefore of the camera) as additional information with each image. This information was recorded by the flight controller for each image at the exact time of exposure which was accomplished by using the shutter signal of the camera for triggering the flight controller's position logging. Additionally, the three-dimensional position offsets of the camera relative to the GNSS antenna (the so-called lever arms) were specified.

Using the auxiliary information mentioned above, the images were aligned in Agisoft Metashape, while the unknown parameters of the camera model were fitted simultaneously. Figure 7 shows exemplarily the position and orientation of each image how it was calculated and optimised by the alignment process in Metashape.

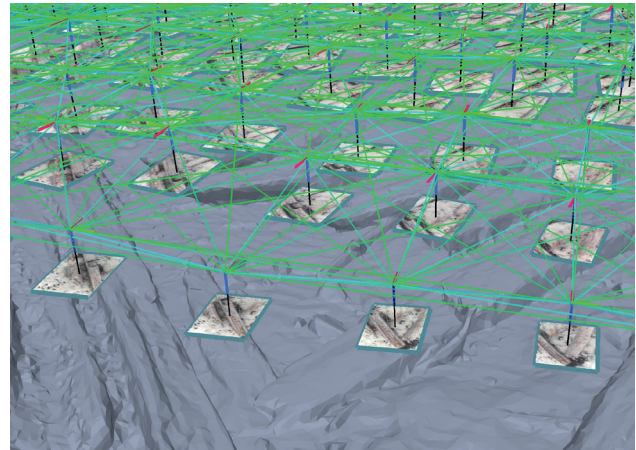


Fig. 7 - Oriented cameras over the 3D model. Irregularities in the position and orientation of the cameras are due to the waves during recording

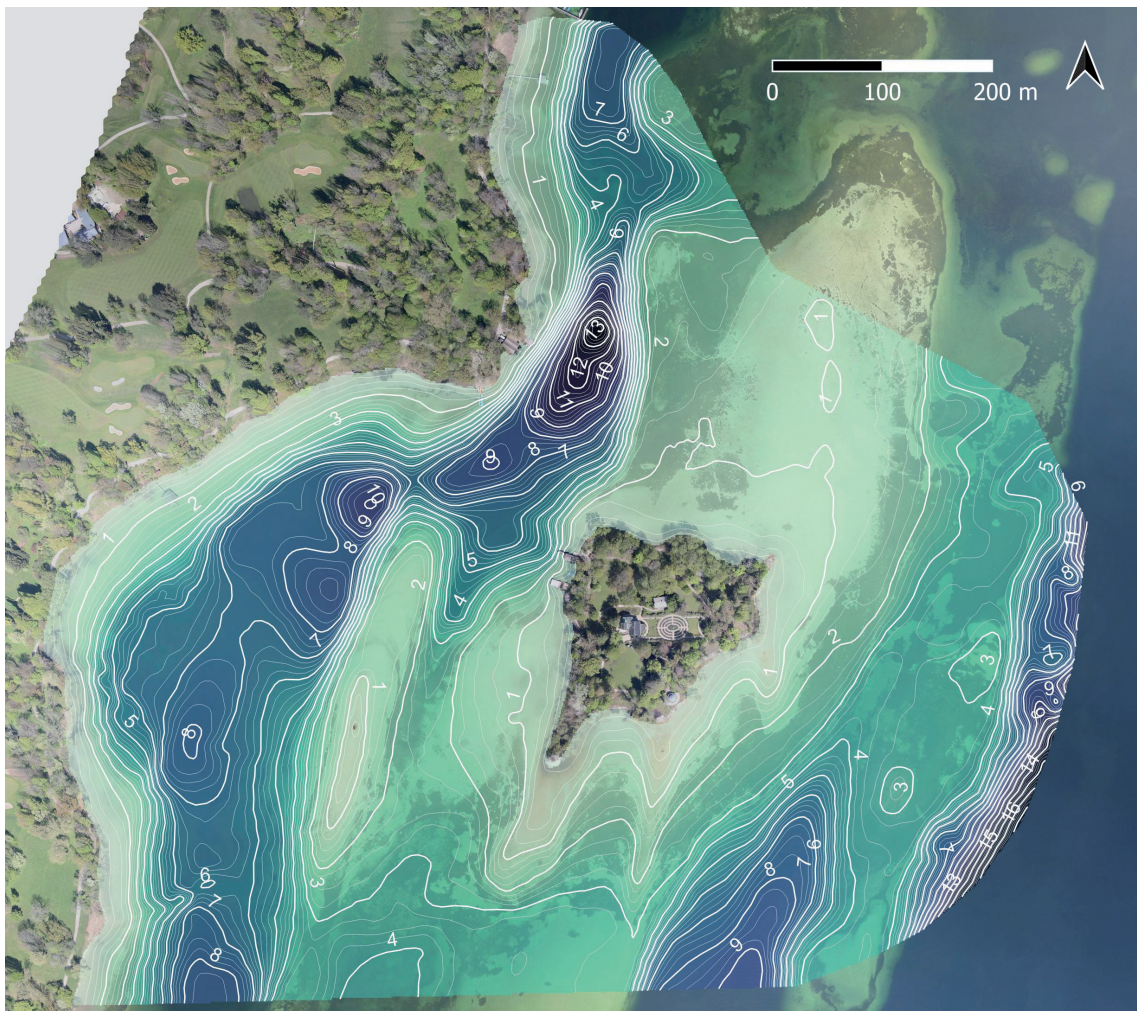


Fig. 8 - Resulting high resolution bathymetric map of the UNESCO World Heritage property and the surrounding buffer zone at Rose Island, Lake Starnberg. Background: Aerial image by DLR

Minor deviations from the rectangular survey pattern, the vertical orientation and position of the camera and an angular deviation from the boat's/camera's longitudinal axis relative to the driving direction can be noticed in Fig. 7. These deviations are caused by the waves during the imaging campaign and are easily calculated and accounted for during the SfM processing.

In order to further increase the geometric precision of the oriented cameras, the known positions of three erosion markers lying in the surveyed area were used as ground control points (GCPs).

RESULTS AND DISCUSSION

Sonar based bathymetric survey

From the pre-processed sonar data, a bathymetric map was generated using the software ReefMaster (version 2.0) (REEFMASER, 2023) and is shown in Figure 8. It is the first complete, accurate map at this level of detail and covers both the UNESCO World Heritage property and the surrounding buffer zone (compare with Fig. 1). It shows a pronounced topography with Rose Island lying on the top of one of multiple submerged moraine ridges dating back to the Last Glacial Period. A pronounced channel, containing multiple and distinct troughs and with a maximum depth of around 14 m separates the island and the other moraine ridges from the mainland. Large parts around the island, especially to the north east, show maximum water depths of only 1 - 2 m. These areas also contain the highest density of archaeological remains.

The indicated depths refer to a water level of 583.9 m above sea level at Rose Island. Note that during all surveys conducted in the scope of this work, the lake levels measured with RTK GNSS lay 30 cm on average below the corresponding values of the only official lake level gauge at the city of Starnberg in a distance of ~7 km from Rose Island. This systematic offset between lake levels measured by RTK GNSS and the gauge at Starnberg could not be explained since both the SAPOS-HEPS service as well as the gauge refer to the German main elevation network DHHN2016.

The depths measured by the sonar (Blue Robotics Ping) were validated against a tape measure at 62 points, covering the whole range of depths occurring in the area from 0 to 14 m. Additionally, the measurements were compared to those of a second sonar (Deeper Chirp+) The setup of the validation survey is shown in Figure 9.

Figure 10 shows a plot of the measurements of both sonars against the readings of the tape measure. The data of both sonars show a very good correspondence with the values read from the tape measure. Since the water temperature affects the speed of sound but was not known over the whole water column, a less linear correlation was expected. However, a diver of BGfU reported a constant water temperature from the surface to the maximum depth of 14 m, which explains the perfectly linear connection between sonar measurements and tape measure readings. The data from the BR Ping sonar showed an RMSE of 0.10 m, while those of the Deeper Chirp+ had an RSME of 0.12 m.



Fig. 9 - Validation of two sonars (Blue Robotics Ping and Deeper Chirp+) against a tape measure at 62 points at different depths

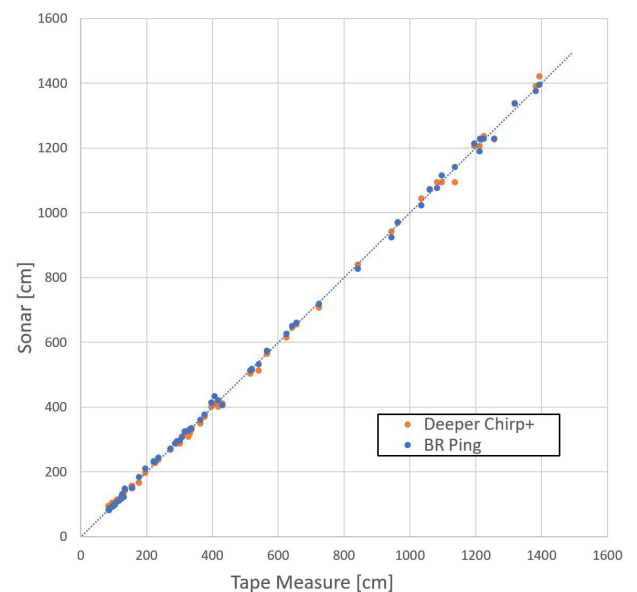


Fig. 10 - Validation of two sonars (Blue Robotics Ping and Deeper Chirp+) against a tape measure at 62 points at different depths

It turned out that possible errors in the depth measurements due to wave-induced pitch/roll movements of the vehicle could be neglected as the sonar beam width of 30 degrees reliably delivered the shortest distance to the bottom in almost all conditions. Minor outliers were compensated by the averaging of five measurements for one data point.

The derived bathymetric map was provided to the TRIQUETRA project partners in the form of vector data (for the isobaths) and as a GeoTIFF raster file with a horizontal geometric resolution of 1 m and a depth resolution of 1 cm. It will be incorporated in the TRIQUETRA DSS as well as in the project's WebGIS.



Fig. 11 - Detail from the 1 mm/pix high resolution textured 3D model of wooden pile dwelling remains at the northeastern tip of Rose Island, where the density of visible archaeological structures is highest

Photogrammetric survey of pile dwelling remnants

From the pre-processed and oriented images of the Celtic pile dwelling remnants at the north-eastern tip of Rose Island (see Fig. 5), a textured 3D model with a per-pixel resolution of 2 mm (1 mm in the area with the highest density of relics) was generated with AgiSoft MetaShape (Fig. 11). The model shows a detailedness and precision way beyond any already existing documentation for this area.

During data processing, no coverage gaps caused by navigational or wave-induced angular deviations occurred since the planned overlap of 80% along track and 60% across-track left some room for such errors. The accurate positional information (nominal error 1-2cm horizontally) provided by RTK GNSS together with the pitch and roll angles recorded by the vehicle's IMU ensured a precise calculation of the camera position and orientation in the SfM process prior to the calculation of the point cloud, thus providing for a closed and accurate 3D model.

The model can be examined in 3D visualization software tools, e.g. the free AgiSoft Viewer. Using the viewers's measurement tool, any distance, e.g. the length of the timbers or the dimension of features like notches or cutouts can be measured (Fig. 12, top). It is also possible to read the state of erosion/accumulation at each

erosion marker contained in the model (Fig. 12, bottom).

In addition, an orthomosaic of the area was generated (Fig. 13). Like the 3D model, the orthomosaic is available at a resolution of 2 mm/pix for the whole area and 1 mm/pix respectively for the area with the highest density of wooden remains.

However, the area covered by photogrammetric methods in this study makes up for only a small part of the 125.000 m² large UNESCO World Heritage property. The bathymetric campaign of 2023 showed that from the total area, 31 % have a water depth of less than 1 m, 66 % less than 2 m and 89 % less than 3 m with respect to a reference water level of 583.9 m AMSL.

Observations from the photogrammetric campaign suggest that the maximum water depth where the SfM method, based on near-surface imagery, is feasible at Lake Starnberg is around 3 m under optimal conditions (clear water during winter and spring). Thus, with the presented technique, it is possible to generate a 3D model of nearly 90 % of the UNESCO World Heritage property at Rose Island.

However, when transferring the method to other regions, the expected turbidity of the water has to be kept in mind as a limiting factor for the depth up to which a photogrammetric survey using a



Fig. 12 - Measuring distances in the 3D using Agisoft Metashape. Top: Detail of a cutout in a sill frame. Bottom: Reading the height of an erosion marker

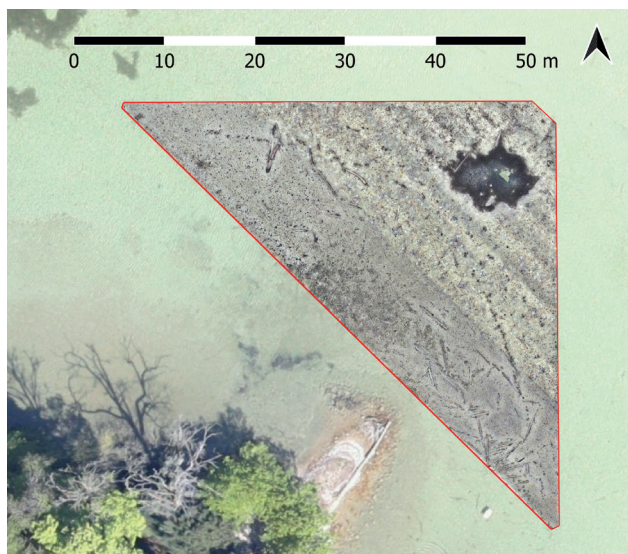


Fig. 13 - Orthomosaic of the area covered by the SfM survey at a resolution of 2mm/pix

USV is feasible. Higher turbidity will cause a lower image contrast which in turn will lead to a lack of image-to-image matching points which are crucial in the SfM process. Image features which don't stand out optically from the background, a general lack of features or repeated patterns of similar features (e.g. regularly shaped ripples in a sandy bottom) will also complicate the identification of matching points and therefore lead to a lower quality point cloud and 3D model. A systematic examination of the effects of turbidity or image contrast in general with respect to the usability of this method was not in the scope of this work.

CONCLUSION

The results of the sonar campaign of 2023 showed excellent quality, both with regard to the depth measurements as well as the derived bathymetric map. The map itself represents a valuable asset and an extremely important piece of information for all further investigations in relation to the threats of climate change like it is done within the project TRIQUETRA but also for any other work in the context of the preservation and management of Rose Island as part of the UNESCO World Heritage site "Prehistoric Pile Dwellings around the Alps". In addition to that, it helps the Nature Protection Authorities to plan and position buoys to further protect the bay of Rose Island as the most important area for resting water birds in Lake Starnberg, which is a Ramsar Wetland of International Importance. In respect to the archaeological remains, simulations of the impact of sinking water levels due to climate change can be conducted in the future and larger scale erosions or accumulations can be monitored by conducting repeated campaigns and comparing their results.

The photogrammetric survey and the generation of an unprecedented, high-precision and textured 3D model showed impressively the value of this method for underwater archaeology. The wooden remains at the north-eastern tip of Rose Island were documented in a most detailed and visually appealing way like it was done never before. Mounting a camera on an unmanned surface vehicle (USV) for gathering large amounts of underwater images in a relatively short time proved to be an effective and efficient approach in order to collect a sufficient number of images for modelling larger areas with the SfM technique. The latter proved once again to be an effective tool for documenting the position, size and condition of relics in the field of underwater cultural heritage exploration. Repeated campaigns, extended to larger areas may help to monitor the degradation of the wooden relics exposed to the water over time, to develop mitigation strategies, and to make decisions regarding protection measures, as a most detailed documentation, e. g., is a precondition before archaeological structures can be covered to protect them from erosion or other threats.

Last but not least, the high-resolution 3D models of prehistoric structures, such as the lying timbers from the Early Celtic period, offer fascinating possibilities for communicating the invisible World Heritage to a broader public, which is an important pillar of the World Heritage protection concept for Rose Island. Currently DLR is preparing a first use of the data for mediation as part of the upcoming special exhibition "Leben unter Wasser" (Life under Water) of Museum Starnberger See, Starnberg (Germany). In addition, the 3D model could be used as part of an XR Experience that brings the invisible World Heritage to life for visitors to the small museum on the island with the help of 3D glasses, or simply as an impressive 3D model that visitors can explore themselves via a smartphone or a web application on their mobile devices.

FINAL REMARKS

Based on the results of the photogrammetric campaign at Rose Island using images taken from the surface using a USV it can be recommended to further develop this method by using more than one camera at the same time for getting a more efficient process during image acquisition. Another improvement would be an optimized survey planning process based on the detailed bathymetric information gained in the survey of 2023. The relatively time-consuming processing of the images to a 3D model can be accelerated by using performant computer hardware and parallelization.

Thus, by optimizing the efficiency of the process as suggested

above, the method could be established as the standard procedure for both monitoring the erosion/accumulation of sediments and the condition of the wooden remnants on a regular basis.

For bathymetric mapping alone, we recommend the use of a bathymetric LIDAR or a multi-beam sonar instead of a single-beam echosounder which would further increase the precision and details of the result and could also be valuable for the year-to-year monitoring of accumulation and erosion processes. For monitoring the state and the detection of changes of the wooden artifacts at Rose Island, the use of a photogrammetric method like the one presented in this article is indispensable.

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