

Article

Surfaced—The Digital Pile Dwellings

Fiona Leipold ¹, Helena Seidl da Fonseca ^{1,*}, Cyril Dworsky ¹  and Ronny Weßling ²

¹ Kuratorium Pfahlbauten, Burgring 7, 1010 Vienna, Austria; leipold@pfahlbauten.at (F.L.); dworsky@pfahlbauten.at (C.D.)

² Crazy Eye 3D-Studio, Schwarzschanerstraße 9/1, 1090 Vienna, Austria; ronny.wessling@crazyeye.at

* Correspondence: seidl@pfahlbauten.at

Abstract: Since 2011, five of Austria's 29 known prehistoric pile dwellings have been part of the transnational UNESCO World Heritage Site "Prehistoric Pile Dwellings around the Alps". These remarkable archaeological sites have been preserved for over 7000 years in lakes and moors. Due to their hidden location underwater or in the soil of bogs, the sites are inaccessible to the public, making it difficult to convey the full scope of this heritage. To address this, the national project "Surfaced—the digital pile dwellings" was launched, aiming to create a virtual bridge connecting the sites, collections, and exhibitions across Austria. It involved digitizing 500 objects, scanned in high resolution, and presenting them as 3D models in an open-access web application. The web application PfahlbauKompass allows users to explore these 3D models, view information about the artefacts and the sites, and create digital collections. It provides access to finds from national museums, regional heritage houses, and private collections. The project offers scientific potential as well as opportunities for virtual exhibitions and educational initiatives. It aims to preserve and visualize an essential part of Austria's cultural heritage and was designed not only to archive finds but also to raise awareness of the hidden sites among the public.

Keywords: UNESCO world heritage; cultural heritage; underwater heritage; 3D digitizing; digital exhibition; prehistoric pile dwelling; science communication; public relations; science mediation; community management



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1. Making an Invisible Cultural Heritage Visible

Since 2011, 111 prehistoric pile dwellings from six European countries have been part of the transnational, serial UNESCO World Heritage Site "Prehistoric Pile Dwellings around the Alps". For 7000 years, extraordinary finds have been preserved at lakes and moors around the Alps. Finds like the oldest wooden wheel in Europe from Južna skupina of the Ljubljana marshes in Slovenia (date 3.150 BC) or one of the oldest wooden doors of the world from Parkhaus Opéra in Zurich, Switzerland (date 3.063 BC) show the significance of the sites. Almost 1000 prehistoric settlements from the Neolithic to the Iron Age are known around the Alps. The archaeological monuments, the material found in them, and their unusually good state of preservation due to the conservation of wet soil are the main characteristics for the outstanding universal value (OUV) of this UNESCO World Heritage Site. The OUV is the cultural significance which is of common importance for present and future generations due to its exceptionality in the world [1]. Five of the twenty-nine currently known prehistoric pile dwellings in Austria are part of the international selection for the UNESCO World Heritage Site. The management of the UNESCO World Heritage Site is organized on a national level within an overarching structure of an International Coordination Group (ICG). In Austria, the Kuratorium Pfahlbauten is the organization

responsible for the national management of the World Heritage Site. It is funded by the federal and provincial governments.

The Kuratorium Pfahlbauten's responsibilities extend beyond basic preservation of Austria's underwater heritage sites [2]. Working with national heritage agency representatives, it implements technical protections and no-anchoring zones on Lakes Attersee and Mondsee [3]. The organization fosters research partnerships, public education, and international collaboration. Key challenges include strengthening legal frameworks, managing tourism impacts, addressing climate change threats, and resolving stakeholder conflicts. Comprehensive monitoring forms the foundation of all protective efforts while raising awareness of these "invisible" sites and encouraging contribution to their long-term preservation and interpretation.

All of the Austrian sites are located below the water surface in the lake beds close to the shore. Due to their hidden underwater location, it is not possible for the general public to visit them on site. Only at information pavilions and protection zone markers are the sites visible in the landscape (see Figures 1 and 2). At exhibitions, visitors have the possibility to see finds from the sites and gain more information. However, the spatial distribution of the sites over several lakes, as well as the storage of the finds in different collections, makes it difficult to convey the entirety of the UNESCO World Heritage Site.



Figure 1. UNESCO World Heritage information pavilion at Lake Attersee.

Since 2011, various methods have been used to draw the public's attention to the vulnerability of the UNESCO World Heritage Site and underwater monuments. By marking the protected areas on the lakes, an attempt is made to make anchoring bans and fishing bans visible to the public. At the same time, different print products explain the necessity of the protection and provide more information on the significance of the sites. With participation at different annual and nationwide events in Austria, like the World Heritage Days on 18 April, the Researchers Night, or the Long Nights of the Museums, the management gets in direct contact with the regional people. By organizing exclusive guided tours for divers to the monument sites (see Figure 3) and "open doors" during field work, access to research and protection activities is given to the public on site (see Figure 4). With citizen science and school projects, public participation can be further expanded and lead to content individually adapted to the respective target group [4].



Figure 2. Buoys marking the protection zone of the UNESCO World Heritage Site at Lake Keutschach.



Figure 3. Guided diving tours to the UNESCO World Heritage Site at Lake Mondsee.

With the project “Surfaced—the digital pile dwellings” (Aufgetaucht—Die digitalen Pfahlbauten), another attempt is being launched at a national level to build a virtual bridge between the sites, the find material, the collections, and exhibition venues in Austria and therefore provide inclusive access to the hidden cultural heritage.

Similar attempts to make the hidden archaeological world heritage visible in virtual space for a broader public have been conducted in the past. For example, in 2021, the international coordination group (ICG) of the UNESCO World Heritage Site management created a digital showcase for the 10th anniversary of the UNESCO World Heritage Site “Pre-historic pile dwellings around the Alps”. In the virtual exhibition “10 Years—100 Stories”, over thirty museums, collections, and archives around the Alps presented objects from UNESCO World Heritage Sites and provided exciting stories about life in prehistoric times [5]. At the national and cantonal level, there are also numerous database systems in which

information on the World Heritage Sites is collected. Most of these have a monument preservation or research focus, such as the AS Portal of Archaeology Switzerland. The AS Portal offers free access to online resources on Swiss archaeology. In this way, new possibilities for using data on valuable public cultural heritage are offered to researchers and monument protection managers. The portal contains the annual find reports of the cantonal authorities (currently 6000 reports) on archaeological investigations on the territory of Switzerland over the last 35 years. In this way, Swiss archaeology offers public accessibility, transparency, and valorization of the work relating to Switzerland's archaeological cultural heritage [6]. However, so far, none of those projects regarding the prehistoric pile dwellings include the integration of a big dataset of 3D models.



Figure 4. Visits from school classes during research activities at Lake Mondsee.

The integration of a large number of 3D objects in virtual exhibitions are well known from other projects, such as the beyond the item project (bITEM) showing famous objects of the Natural History Museum Vienna, like the Venus of Willendorf. On the bITEM website, stories of famous objects from the museum are revealed on digital twins. The interactive platform was developed by a multidisciplinary team and invites you to explore exciting stories about the objects through appealing functions. bITEM is aimed at anyone interested in cultural heritage and sheds light on the captivating biographies of important artefacts and exhibits [7]. A similar approach was also taken in the implementation of the project “Surfaced—the digital pile dwellings”.

The project was implemented as part of the Kulturerbe Digital (cultural heritage digital) funding program. The aim of the funding program was to make Austria's cultural heritage more usable and accessible to a broad national and international public with the help of digital technology. Funding was provided for the digital preservation of collection objects; their digital recording, cataloguing, publication, presentation, and dissemination; as well as the development of online collections. The funding program is part of the Austrian recovery and resilience plan and is financed by EU funds [8,9].

2. The PfahlbauKompass—Digitizing and Networking

The beginnings of pile dwelling research and of the collection of finds date back to the 19th century. With the discovery of the first lakeshore settlements, a veritable “pile-

dwelling fever” broke out in Europe. It is therefore not surprising that the finds from these are spread across many collections. In 2023, the funding program Kulturerbe Digital provided a good opportunity to bring them together again, at least to a certain extent. From 2023 to 2024, 367 objects (3D) and 133 documents (2D) were scanned in high resolution from different collections. In total, finds from ten collections were included in the digitization, most of which are publicly accessible at large national museums; small, regional heritage houses; and university study collections. However, private collections were also included, the contents of which would otherwise remain completely hidden from the public (see Figure 5).



Figure 5. Private collector Kurt Schaefer with prehistoric finds from underwater sites of Upper Austria, picture: estate of Kurt Schaefer, Kuratorium Pfahlbauten.

To provide a meaningful context, it was necessary not only to make the models publicly accessible but also present additional information about their origin. Therefore, the most up-to-date and publicly accessible presentation of the results was planned and implemented at the same time as the digitization of the finds. On the one hand, the project “Surfaced—the digital pile dwellings” was developed to save the find material in the form of digital twins and thus preserve it for the future. On the other hand, the generated 3D data offer the possibility of providing access to the pile dwelling finds in various ways. The goal was to develop a “pile dwelling museum for your pocket”—the PfahlbauKompass.

From the very beginning of the project, the focus was on communicating the findings. This aim was based on the following different goals:

- Showing the pile dwellings in all their diversity;
- Returning objects to the region of their origin;
- Preserving organic material;
- Emphasizing the European dimension;
- Enabling location-independent access;
- Creating didactic documents;
- Communicating the finds in their spatial dimension and context;
- Visualizing the position and circumstances under water.

2.1. The Selection of Finds—What to Choose?

The selection of finds was made in cooperation between the local curators of the collections, 3D Studio Crazy Eye, and Kuratorium Pfahlbauten. The selection was not based purely on aesthetic considerations; the aim was to provide an overview of the range of finds from the prehistoric settlements, as complete as possible. This broad spectrum of finds, with excellent organic preservation (see Figure 6), distinguishes the pile dwellings within most archaeological sites and is one of the main aspects of the Outstanding Universal Values of the prehistoric pile dwellings [1].

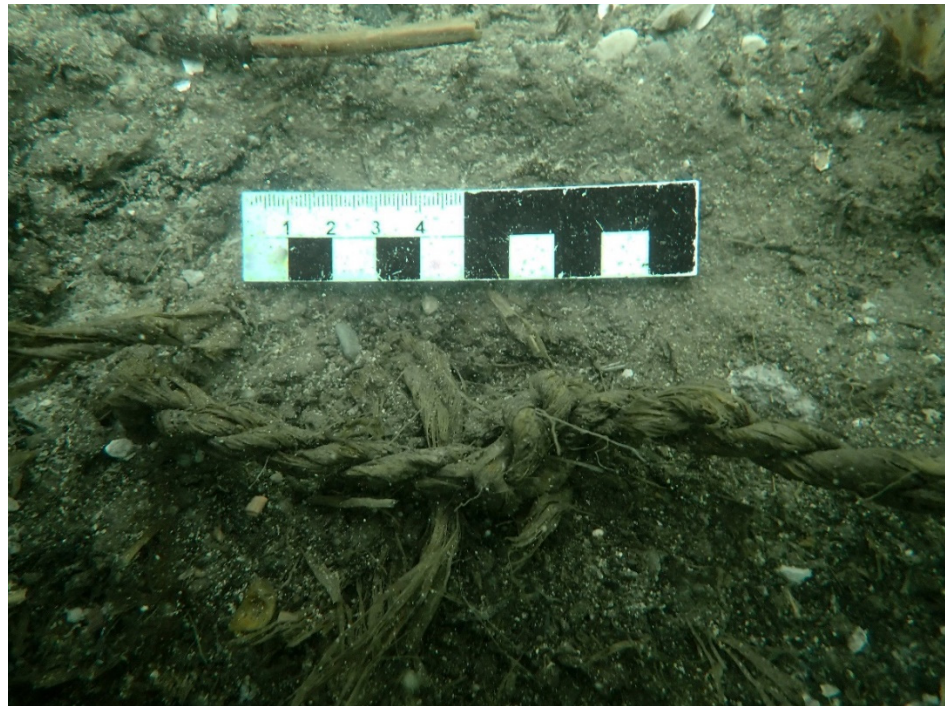


Figure 6. A raffia rope with a knot from the Late Neolithic site Mooswinkel, Lake Mondsee.

However, the selection of finds was also influenced by external conditions. In the case of some smaller museums of local history, which are maintained by voluntary association activities, it was also difficult to find contact persons for the implementation of the project. During the visits to the small and regional heritage houses, it soon became clear that not all objects are easily available for documentation. Some finds were almost sealed in the display cases, which would have had to be broken open to reach the objects. Despite the logistical and organizational effort involved, direct contact opened the possibility to pass on the benefits and potential applications of the project results to the relevant collections. The needs and possible applications of those responsible on site were incorporated into the design of the end product, and the content and function relevant to them were considered. Therefore, this process was a good opportunity to expand the network and develop better community management.

The final selection represents only about 1–2% of the total Austrian find material and thus represents a relatively small digital archive. However, the digitized copies include all types of material from various sites in Austria.

2.2. The 3D Models—Methodology and Standards

The 3D scanning and model preparation were carried out by 3D Studio Crazy Eye. In this project, different approaches were used: image-based modelling (IBM) incorporating structure-from-motion and multi-view stereo algorithms and structured-light 3D scans.

Although the use of structured-light scanners is effective and offers a high level of geometric accuracy, there are deficits in terms of texture quality (see Figure 7).

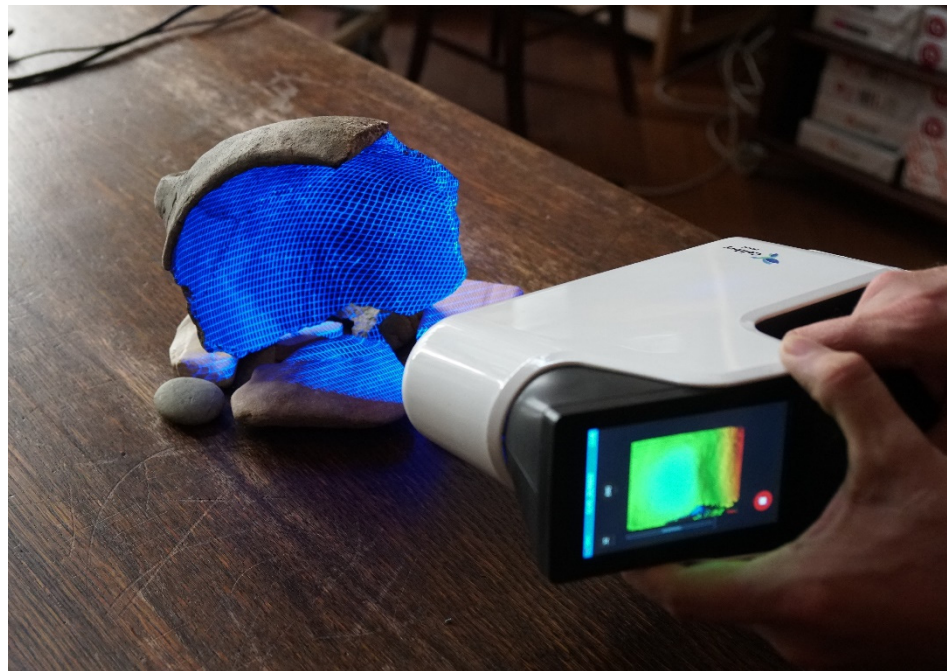


Figure 7. Scanning process with structured light.

The selection of the respective scanning method was based on the following criteria:

- Importance of the object for the site;
- Importance of a photorealistic texture for the presentation of the object, for example, if very fine superficial structures, such as fingerprints, are to be visible on the object.

If one of the two criteria were classified as high, the object was scanned using IBM. Otherwise, a handheld structured-light 3D scan was performed.

For the Image-Based Modelling (IBM) capture of medium- and large-sized archaeological finds, a specially developed setup was employed (see Figure 8). The use of the cross-polarization method effectively eliminated surface reflections, while a self-driven turntable enabled a semi-automated and thus cost-efficient scanning process. Organic remains, such as fish bones, seeds, and fruits, as well as small artefacts like beads or spindle whorls with dimensions of less than 0.01 m, were scanned using the open-source scanner scAnt. This scanner, originally developed by Imperial College London for the 3D scanning of insects, proved to be well-suited for capturing high-resolution models of these delicate and minute objects [10].

Regarding scan resolution, a balance between accuracy and speed was consistently maintained, depending on the significance and importance of each artifact. The primary objective was to capture a faithful virtual representation of the objects, with a focus on geometric precision and optimal texture reproduction.

During digitization, care was taken to create long-term, high-quality models so that even the smallest ornamental details or traces of prehistoric processing are visible in the finished model. Thus, the digitized copies are suitable for scientific investigations as well as for virtual exhibitions and educational projects. For web-based visualization, the quality was reduced to a standard of 1 million faces and a texture atlas of $12,144 \times 12,144$ pixels. The 3D digital copies provided can not only be 3D printed for haptic visualization, but the digital twins can be used for scientific questions. On the digital objects, superficially

visible traces, such as prehistoric traces of processing, can be examined without having to travel to the place where the object is located. In this way, the digitized copies can facilitate selection processes for further scientific investigations. In addition, the data can be useful for deriving further images, redrawings, and drawings of profiles. With the addition of further 3D scans, the data can be used for AI-based classification and typology. Even if no collection is currently completely recorded and the PfahlbauKompass is therefore insufficient for statistical evaluations and complete search queries on certain types of archaeological material, it contains all existing public collections in which finds from pile dwelling sites in Austria can be found and represents all previously known pile dwelling sites from Austria. In this way, it provides scientists with a good overview of the distribution of finds in the respective collections and reflects the current state of pile dwelling research in Austria.



Figure 8. Scanning process with image-based modelling (IBM).

3. The Web Application—Information and Access

PfahlbauKompass is a web application that offers the possibility to view the pile dwelling objects and get information about the prehistoric artefacts, the time of their use, and the pile dwellings themselves [11]. This is a form of digital collection explorer and was programmed by the digital agency lowfidelity Heavy Industries using Drupal. Users can search for specific objects, create their own digital collections of 3D models (embedded from Sketchfab), and download them for printing. In addition, PfahlbauKompass contains basic information on the prehistoric pile dwellings in Austria and the transnational UNESCO World Heritage Site. It is therefore not just a 3D object archive but resembles a virtual exhibition for your pocket. Users not only get an overview of the available material but also the contact points for further studies.

The aim was to achieve the greatest possible overlap between the many different target groups in terms of usability. Researchers, laypeople, interested parties, and newcomers should be able to find their way around the application. It should be easy and intuitive to access specific information on the individual artefacts as well as on the lakeshore settle-

ments, their geographical and spatial context, and their status as a UNESCO World Heritage Site. Since the project was funded by the Austrian Federal Ministry, the focus was on the inclusion of national collections, and the national language also had to be considered for the virtual exhibition of the objects. For this reason, the content is currently only available in German. However, since it is a web-based program, any translation program installed in the browser can be used to have the information translated into the desired language. In addition, the web application is technically designed to enable a multilingual presentation of the content in a further expansion step.

The collection of digitized finds is equipped with a complex filter function that allows users to approach the application with specific questions. After registering, it is also possible to create user-based collections with favoured finds (see Figure 9). As mentioned before, the 3D models are also accessible to the public, and the OBJ files can be downloaded for free and printed out in 3D.

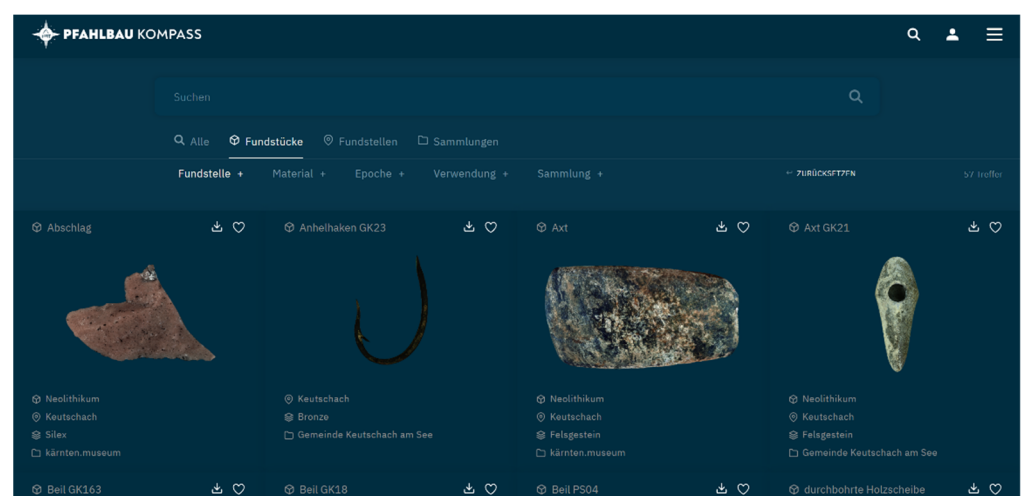


Figure 9. The filter function from the PfahlbauKompass allows for a comprehensive query by material, epoch, location, collection, and use of the object.

The metadata of the finds were researched and collected according to the specifications of Kulturpool Österreich [12]. The submission data contains the most important information about the objects, such as the name of the object, the description of the material, the date of the object, and the archaeological cultural group, as well as information about the place of discovery and the collection: name of the site and region, name of the collection, and the address of the current collection ownership. For the exhibition in the PfahlbauKompass, additional information and text elements were designed to tell users of the web application exciting stories about the objects, the sites, and the research. In an expansion variant, it is also possible to set certain markers within the 3D models, in which special features of the objects can be pointed out, similar to the 3D Museum of the Natural History Museum Vienna [13]. These data are provided with generally understandable, short information texts, which are intended to give the public a better overview of the range of materials used in prehistory that have been preserved in the wetland settlements.

4. Future Prospects

The project digitizes, secures, and visualizes an outstanding part of the cultural heritage in Austria. In 2024, it was honoured with the Creative App Award at the Cultural Heritage and New Technologies Conference (CHNT) in Vienna. However, the final product is only the beginning for the application. It is designed to be updated regularly, to grow, and to be filled with further content. The maintenance of the app is part of the management tasks

of Kuratorium Pfahlbauten. This should happen together with the responsible curators as well as other participants from the regions and the circle of interested parties around the pile dwellings. This is particularly important, as participation in the World Heritage Site is a key aspect of the management work, and the applications should be further customized for the users.

In order to not only reach as many people as possible with the app but also to integrate them and strengthen their identification with it, various measures are possible in the future. For example, the planned student internship “World Heritage served digitally” (Welterbe digital serviert, FFG Talentepraktikum 2025 from 14 July to 8 August) is intended to familiarize young people with the professional and technical aspects of the PfahlbauKompass and expand the content of the virtual exhibition. Results and research from students’ final theses can be incorporated. Local historians can feed their knowledge into it. The open-access contributions will be managed by the Kuratorium Pfahlbauten, with the PfahlbauKompass serving as a community management tool.

Various associations and museums can use the app and the content generated for it (also separately) for their guided tours and exhibitions. Smaller projects will not only expand the (3D) content but also improve the storytelling of the app. Through further gradual development, good promotion, and involvement of the general public, PfahlbauKompass could develop from a very specialized and technical application into an entertaining tool for imparting knowledge and arousing curiosity about the cultural heritage of pile dwellings.

The future will show to what extent the PfahlbauKompass and the individual digital elements will actually be used by a broader public. In addition, the recording of accesses and downloads, since the web application is publicly accessible, is to be a basis for further evaluations.

5. Conclusions

The “Surfaced—the digital pile dwellings” project represents a significant advancement in making Austria’s underwater cultural heritage accessible to the public. By digitizing 500 objects from various collections and creating the PfahlbauKompass web application, the project establishes a virtual bridge connecting prehistoric pile dwelling sites, artefacts, and exhibitions across Austria. This initiative not only preserves these remarkable archaeological treasures as digital twins but also democratizes access to cultural heritage that would otherwise remain hidden beneath lake surfaces or scattered across diverse collections. The collaborative approach involving national museums, regional heritage houses, and private collections demonstrates the power of digital technology to unify disparate cultural resources. Beyond mere archiving, the project fosters community engagement, supports educational initiatives, and provides a platform for scientific research. As part of Kuratorium Pfahlbauten’s ongoing management responsibilities, the PfahlbauKompass is designed to grow and evolve through continued participation from curators, students, local historians, and the broader public, ensuring that this UNESCO World Heritage Site remains relevant and accessible for future generations while addressing the fundamental challenge of making an invisible heritage visible.

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Data Availability Statement: The 3D data of the scanned objects can be downloaded at the web-application PfahlbauKompass (kompass.pfahlbauten.at, accessed on 13 March 2025). All digital data are also accessible at Kulturpool Austria (kulturpool.at, accessed on 13 March 2025).

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Conflicts of Interest: Author Ronny Weßling was employed by the company Crazy Eye 3D-Studio. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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