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# 3D MASS DIGITIZATION: A MILESTONE FOR ARCHAEOLOGICAL DOCUMENTATION

***DIGITALIZACIÓN MASIVA EN 3D: UN HITO PARA LA DOCUMENTACIÓN ARQUEOLÓGICA***

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**Abstract:**

In the heritage field the demand for fast and efficient 3D digitization technologies for historic remains is increasing. Besides, 3D digitization has proved to be a promising approach to enable precise reconstructions of objects. Yet, unlike the digital acquisition of cultural goods in 2D widely used today, 3D digitization often still requires a significant investment of time and money. To make it more widely available to heritage institutions, the Competence Center for Cultural Heritage Digitization at the Fraunhofer Institute for Computer Graphics Research IGD has developed CultLab3D, the world's first fully automatic 3D mass digitization facility for collections of three-dimensional objects. CultLab3D is specifically designed to automate the entire 3D digitization process thus allowing users to scan and archive objects on a large-scale. Moreover, scanning and lighting technologies are combined to capture the exact geometry, texture, and optical material properties of artefacts to produce highly accurate photo-realistic representations. The unique setup allows shortening the time needed for digitization to several minutes per artefact instead of hours, as required by conventional 3D scanning methods.

**Key words:** fast and economic 3D digitization, cultural heritage, documentation method, technological innovation, industrialization, automation

**Resumen:**

La demanda de tecnologías rápidas y eficientes en el área de digitalización en tercera dimensión para el legado cultural, se encuentra en constante crecimiento. La digitalización en tercera dimensión ha mostrado ser una aproximación prometedora que garantiza una precisa reconstrucción de objetos. Sin embargo, en comparación con la adquisición de objetos culturales en 2D, ampliamente utilizados en la actualidad, la digitalización en tercera dimensión aún requiere de una inversión significativa de tiempo y dinero. Para facilitar su acceso a instituciones enfocadas a salvaguardar el legado cultural, el Centro de Competencia para la Digitalización del Legado Cultural (Competence Center for Cultural Heritage Digitization) del Instituto Fraunhofer, Computer Graphics Research IGD, desarrolló CultLab3D. CultLab3D es la primera instancia a nivel mundial que cuenta con un sistema totalmente automatizado para la digitalización masiva de colecciones de objetos tridimensionales. CultLab3D se diseñó específicamente para automatizar los procesos de digitalización en tercera dimension, permitendo escanear y archivar objetos a larga escala. Además, tecnologías de escaneado e iluminación han sido igualmente combinadas para la captura de geometrías exactas, textura y propiedades ópticas del material que constituyen los artefactos en cuestión, con el objetivo de producir representaciones foto-realísticas altamente precisas. Esta construcción única permite la reducción del tiempo requerido por métodos convencionales para la digitalización en tercera dimensión, siendo necesario solamente algunos minutos en lugar de varias horas.

**Palabras clave:** digitalización 3D rápida y eficiente, herencia cultural, método de documentación, innovación tecnológica, industrialización, automatización

## 1. Introduction

Innovative documentation methods for heritage remains are becoming increasingly important. This heightened relevance results from both the desire to provide better access to unique objects, e.g. to make collections more easily available for research or to a wider audience, and the looming threat of losing them due to disasters and other environmental influences. In the past, intensive efforts have been made by collecting institutions to digitize books, photos and other works of art and digitization has proved to be a promising approach to create precise reconstructions of heritage objects for their digital preservation and virtual representation. However, so far automated digitization has been developed and implemented only for "2D" artefacts that can largely be found in libraries and archives. Because the process is still slow and highly manual, digitizing

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objects in 3D continues to be a tedious task reserved for only a few selected objects. This drawback impedes the 3D digitization of larger collections with numerous three-dimensional objects such as zoological and archaeological finds or everyday objects from cultural-history museums.

Against this background, the Competence Center for Cultural Heritage Digitization at the Fraunhofer Institute for Computer Graphics Research IGD developed CultLab3D (CultLab3D, 2016) in an interdisciplinary research project. The system is one of the first feasible approaches worldwide to enable fast, efficient and cost-effective 3D digitization. It is specifically designed to automate the entire 3D digitization process and thus allowing users to scan and archive large amounts of heritage objects for documentation and preservation.

## 2. The need for 3D digitization

Article 3.3 of the European Union Lisbon Treaty (Treaty of Lisbon, 2007) stipulates that "Europe's cultural heritage is safeguarded and enhanced" for future generations. Nevertheless, cultural heritage is often at risk to be damaged and compromised in value. How fragile it really is has been made apparent by several natural and man-made disasters. Incidents such as the recent intentional destruction of the ancient Semitic city Palmyra, Syria, and the archaeological finds at the museum in Mosul, Iraq, underline the need for new documentation methods and have led to a re-evaluation of the importance of high-resolution facsimiles.

By acknowledging the value cultural heritage has for the richness of the world's history and identity, comprehensive measures have been taken for years on international level to advance the digital documentation and preservation of historic assets on a broad scale. Notable examples are the Google Books Library Project, the Google Art Project, the German Digital Library (German: *Deutsche Digitale Bibliothek*) or Europeana (Google Books Library Project, 2016; Google Art Project, 2016; German Digital Library, 2016; Europeana, 2016). This cultural platform – and at the same time – digital library, archive and museum was launched in 2008 with the aim to consolidate all national digital libraries under one roof and to make historic inventories and collections in digital form widely available to the public. Another first approach to comprehensive 2D digitization was developed by Picturae, a Dutch company specialized in scanning cultural heritage items. Its first commercial, automated conveyor belt setup bases on digital photography and successfully allows scanning of heritage material such as herbarium sheets on a large scale and at high speed (Picturae, 2016).

These activities have led to new technologies for mass digitization but mostly they remain constrained to two-dimensional objects such as books and paintings or focus on digital items such as videos, films, photographs or audio recordings. While digitization in 2D is already implemented on a wide scale and in high efficiency, 3D acquisition is still costly in terms of time and money. Digitizing three-dimensional objects such as archaeological finds like bronzes, iron artefacts, wooden objects, ceramics or busts in 3D therefore mostly focuses on prestigious individual cases rather than on entire series. In this context, the term '3D digitization' refers to the digital capture of a three-dimensional object with its shape and its visual appearance from all possible angles. For this reason, a digital replication in 3D is different to a photograph, "seeking to map the complete geometry of an object, its surface texture and where possible its visual material characteristics, and combining these to produce an integrated digital 3D model that depicts the object as accurately as possible". Contrary to a 3D replica, which can be viewed from any angle, a photograph is a static image of an object taken from only one specific perspective (DFG, 2013).

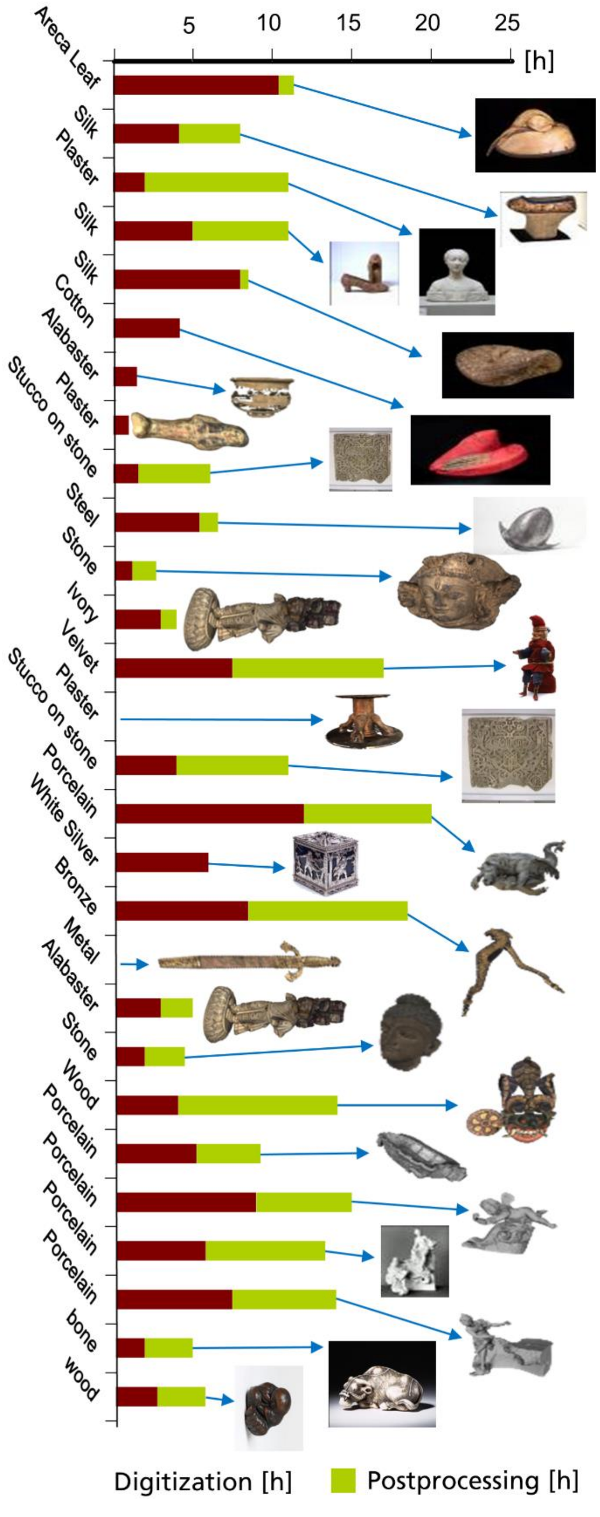



**Figure 1**: Study: Victoria & Albert Museum – acquisition time including post-processing for different geometries and materials.

Capturing an artefact in 3D is technically challenging, in particular if it targets a faithful reproduction of its geometric complexity and its optical material properties. According to studies taken place at the Victoria and Albert Museum in London within the EU project 3D-COFORM (Echavarria et al., 2012), 3D scanning of an object including the post-process takes from several hours to a day or more on average (see Fig. 1). Time varies greatly for geometry and texture acquisition and does not even consider complex materials. The process requires a considerable amount of manual work (up to 85% of the total time), mainly required to re-position the sensor devices. The repositioning time effort strongly depends on the size of the artefact, its complexity and the presence of geometric occlusions.

In addition, no commercially available 3D technology for scanning large amounts of objects and producing color calibrated 3D virtual models has been developed until now, resulting in the growing need for cost-effective and fast scanning solutions with high output. At the same time, the demand to capture three-dimensional artefacts has grown. Recognizing the value added by 3D scanning, cultural heritage institutions begin to leverage and understand its potential for stimulating innovation. Having proved to be promising and innovative, 3D digitization not only enables a precise reconstruction of heritage objects for documentation and preservation. It also offers new ways of presentation that will change the cultural heritage domain: new visualization and interaction technologies allow heritage experts or curators to display and share collections or research results in novel ways both on-site in a museum setting as well as online. Especially the ways afforded to better present artefacts online gives institutions the chance to achieve greater visibility for their collections and engage with a wider audience.

3D digitization offers a range of benefits and can therefore add value in the cultural heritage sector by enabling new forms of participation and a broad range of new applications, services and business models in areas such as education, tourism or gaming to attract new audiences:

### 2.1. Accessibility

3D replicas allow for global digital access to collections and research results. Numerous objects, of which only a fraction is displayed in museums for example, can be scanned, classified and documented in online catalogues making them accessible to education and the public at large. 3D replicas can be made available easily and therefore accessed by several researchers at once. Also they pave the way for new research methodologies. For example, fragments of complex fossils can be reassembled correctly with the aid of 3D models or archaeologic objects scanned in situ and analyzed immediately.

### 2.2. Conservation

High-quality 3D virtual models can be used by conservators as a reference for conservation and restoration measures on damaged goods and serve as a basis to generate physical replicas. Furthermore, a 3D model can help to precisely visualize damage patterns or worn areas and thus support better restoration decisions. In addition, high quality virtual exhibits in many cases can replace the shipping and loaning of originals to exhibitions, eliminating the risk of further deterioration due to accidental damages or detrimental environmental conditions and high insurance costs.

### 2.3. Documentation

Significant pieces of art which are endangered by environmental influences or even irrevocably destroyed by disastrous events may at least be secured in their current state of conservation and made accessible for research around the world. In case of the loss of an original, the image, form and context are still available for scientists and interested parties by means of photo-realistic 3D models. With the aid of such digital '3D conservation' objects remain accessible for subsequent generations.

### 2.4. New exhibition formats

3D models open up new ways of exhibition planning and implementation. Collections spreading over multiple museums can be showcased concurrently at different geographic locations. Virtual reproductions can be used in hybrid exhibitions and create innovative and interactive visitor experiences. Collections and exhibits become accessible for visitors from anywhere in the world and enable new ways of interaction with collections. 3D models can also be presented through purely virtual museum experiences and even allow for customized 'digital exhibitions at home'.

### 2.5. New applications and services

3D replicas are available for development of apps, games, documentaries, tourism services and educational content and can thus ensure a more intense visitor experience, new forms of participations and additional revenue streams.

### 2.6. 3D print

3D replicas, materialized in 3D printed form, are usable as exhibition and loan objects for various purposes (i.e. to avoid damages and insurance costs or legal uncertainty relating to ownership). Not only delicate or particularly fragile artefacts but also those too valuable for transport or loan lend themselves to the creation of copies true to the original. High-precision printing models developed from the collected 3D data can serve the physical reproduction of destroyed or fragmented cultural heritage goods.

## 3. CultLab3D – First approach to 3D mass digitization

CultLab3D is a multi-modular 3D mass digitization pipeline composed of individual scanning stations that work stand-alone as well as together as an integrated system. The long-term vision is to enable the generation of consolidated 3D models fusing geo-referenced results of a variety of different digitization approaches ranging from surface scanning methods such as photogrammetry, structured light or time-of-flight to volumetric scanning technologies such as ultrasound, MRI and CT. In addition to the volumetric and surface geometry and the appearance of artefacts, information on the conservation state can be gathered through mass-spectroscopy or chemical analysis. The underlying design principle of CultLab3D as a flexible and extendable scanning system is that each additional station improves the quality of the overall scan, increases the throughput of the overall pipeline or adds new information to the consolidated 3D models generated. Artefacts are passed from one scanning station to another using transparent carrier trays moved by conveyor belts (see Fig. 2).

**Figure 2**: Fraunhofer IGD's CultLab3D pipeline system at the Liebieghaus Skulpturensammlung. "Apollo Belvedere" (1497/98) by Renaissance sculptor Pier Jacobo Alari Bonacolsi (ca. 1460-1528), called Antico, on the mobile digitisation lab. Liebieghaus Skulpturensammlung's Medieval Hall. Photograph: Norbert Miguletz © Liebieghaus Skulpturensammlung.

In its current development state CultLab3D focuses on the capture of geometry, texture and optical material properties and consists of two modules, CultArc3D and CultArm3D.

CultLab3D is color calibrated and the processing sequence fully automated:

- An artefact is placed upon a transparent tray;
- A QR code reflecting the object's inventory number is shown to a controller tablet PC;
- The scan process starts and the tray is moved into CultArc3D;
- 153 pictures from above and 9 from below are shot within a minute and then sent to the 3D model preview computation which will take 5 minutes;
- In parallel to this process 144 additional pictures are captured from interleaved positions;
- Then the artefact is moved to the CultArm3D while the next artefact can enter the pipeline;
- The 3D color calibrated preview model computed indicates remaining holes and occlusions yet to be covered by the CultArm3D;
- Once the artefact is positioned at the center of the turntable of CultArm3D, the two parts of the photo booth close and the remaining holes and occlusions are automatically scanned by a camera mounted on a robotic arm. The optimal trajectory guiding the camera from one view to the next is generated using a next-best-view algorithm;
- Once capturing at the CultArm3D scan station is complete, the artefact is moved to the end of the pipeline;
- Final offline 3D reconstruction takes place using all images from CultArm3D and CultArc3D.
- The throughput of the pipeline is 10 minutes per artefact for geometry and texture acquisition.

### 3.1. CultArc3D

CultArc3D is an image-based scanning device consisting of two arcs, a light arc comprising nine equiangular ring lights and a camera arc comprising nine equiangular 10 MP USB3 cameras, both covering a hemisphere around an artefact on a carrier tray at CultArc3D's center while their radii differ to allow independent rotation and a number of stop positions at discrete angles. To capture the bottom-side of artefacts through the transparent carrier tray another nine cameras identical to the ones on the camera arc are statically installed below, as well as two opposing light sources, illuminating the object homogeneously from below. To allow free view from below and at the same time guarantee safe positioning of the trays at the center, CultArc3D uses a retractable bridge between two connected conveyor belt segments (see Fig. 3).

CultArc3D's design allows capturing geometry, texture and material properties and is inspired by related work in the field. Structured light technology has been used in surveys undertaken by (Gorthis & Rastogi, 2010) and (Salvi, Fernandez, Pribanic, & Llado, 2010) on 3D geometry and texture acquisition. (Weyrich, Larence, Lensch, Rusinkiewicz, & Zickler, 2008) described how to measure the spatially and directionally varying reflectance and subsurface scattering of complex materials and how to store BRDFS and BSSRDFs. Setups to capture geometry, texture and optical material properties can range from very simple to very complex setups differing significantly regarding their performance. (Holroyd, Larence, & Zickler, 2010) move a co-axial setup of a camera and a light-source around an artefact during acquisition with an identical setup looking down on the artefact from above. (Schwartz & Klein, 2012) use a multiview/multilight setup of 151 consumer cameras and LED lights called the DOME to capture the shape as well as the appearance model of an artefact's surface. In its improved version (Schwartz, Weinmann, Ruiters, & Klein, 2011) 11 industrial high resolution video cameras mounted on a vertical quarter-arc revolving inside the DOME replace the consumer cameras and LED lights replace the consumer camera's flashlights. While acquisition time is slightly higher the quality of the results has notably improved. At DFKI (Kohler, Noell, Reis, & Stricker, 2013) have built the ORCAM (Noell, Koehler, Reis, & Stricker, 2015), a fully spherical setup similar to the DOME which in addition to the previously mentioned setups is able to capture the bottom-side of artefacts by placing them on a transparent, rotational, anti-reflective glass carrier, pivo-mounted on a steel ring. High-resolution DSLR photo cameras and a structured light projector revolve around the sphere capturing geometry, texture and optical material properties. On average, acquisition of geometry, texture and optical material properties takes an hour for objects up to 80 cm of diameter.

Currently, CultArc3D allows for two distinct capturing modes. When acquiring 3D geometry and texture only, both arcs move in synchrony and stop at nine equiangular positions on the upper hemisphere around their joint rotating axis, resulting in $9^2 = 81$ images being

**Figure 3**: CultArc3D at the Liebieghaus Skulpturensammlung. “Apollo Belvedere“ (1497/98) by Renaissance sculptor Pier Jacobo Alari Bonacolsi (ca. 1460-1528), called Antico, on the mobile digitisation lab. Liebieghaus Skulpturensammlung‘s Medieval Hall. Photograph: Norbert Miguletz © Liebieghaus Skulpturensammlung.

**Figure 4**: CultArm3D, part of CultLab3D at Digital Heritage 2015 in Granada, Spain. CultArm3D is used to resolve remaining occlusions or holes not covered by the first scanning station CultArc3D.

taken that can be used for photogrammetric 3D reconstruction of the artifact. When 3D geometry, texture and optical material properties are acquired, both arcs move independently such that all discrete combinations of evenly distributed camera and light positions on the upper hemisphere around an artifact are captured, resulting in $9^4 = 6561$ images being taken. The acquired image set can be used for both photogrammetric 3D reconstruction of an artifact and to compute its optical material properties. After completion of each mode the arcs move into the upright position and the artefact moves out of the CultArc3D module. A particularity of CultArc3D, already used with natural history dinosaur bone findings, is its ability to scan long objects of theoretically unlimited length. For this purpose the front of an object is acquired by the arcs moving in synchrony along the first half of the capturing hemisphere until reaching the upright position. While the image acquisition process continues with the arcs in upright position the object is moved underneath. Finally, the back end of the object is captured by the arcs moving in synchrony from the upright position along the second half of the capturing hemisphere to the bottom.

### 3.2. CultArm3D

CultArm3D is a lightweight and compliant scanning robot at a turntable with either the same type of camera and ring light attached to the end-effector of its arm as the ones used in the CultArc3D, or as an extension for higher quality, a camera with a higher resolution sensor in combination with diffuse light boxes mounted around the turn table. The CultArm3D (see Fig. 4) can also be used as a standalone unit to scan arbitrary objects of a shape prior unknown to the system. To this end, a real-time next-best-view algorithm has been developed which, beginning with a first scan of the artefact, calculates the next best views and thus an optimal trajectory for the robotic arm to follow in order to allow for optimal capturing of required camera views.

The CultArm3D is able to scan an entire object with the least number of views while covering its entire surface. Further, the very same algorithm can also be applied to each of the remaining holes, occlusions and locations of higher geometric complexity found in the fast initial 3D reconstruction of the object coming from the CultArc3D.

Several studies have been made on automated 3D reconstruction using robots (Kriegel, Bodenmüller, Suppa, & Hirzinger, 2011; Scott, Roth, & Rivest, 2003; Shi, Zhang, Xi, & Xu, 2009) with scanners mounted on their end-effectors. However, most of the times heavy-duty industrial robots are used in large workspaces focusing on “blind” acquisition of geometry along predefined trajectories only (e.g. car industry), whereas in our case the workspace for our compliant, lightweight robotic arm is far more limited and we focus on autonomous dynamic scan planning methods.

Kinematic accessibility is the key for trajectory planning, therefore inverse kinematics solver techniques must be used. The field is divided in geometric/analytical exact methods (Gan, Oyama, Rosales, & Huosheng, 2005) and iterative methods (Kenwright, 2012; Toshani & Farrokhi, 2014). For our work we have chosen to implement the closed-loop inverse kinematics (CLIK) algorithm (Siciliano, Sciavicco, Villani, & Oriolo, 2009). Using the Lyapunov (Lyapunov, 1992) method we can ensure asymptotic stability of the system.

For each hole and occlusion in the fast preview scan calculated based on CultArc3D’s output, a next-best-view planning has to be performed. A volumetric representation of the preview scan is used to analyze local point cloud density and normal vectors where good local quality estimates can be distinguished from bad estimates, e.g. areas with low image coverage due to occlusions or poorly textured surfaces where insufficient features were found (see Fig. 5). Subsequently the bad local estimates are the most appropriate candidates for additional views. As opposed to approaches with structured light (Karaszewski, Sitnik, & Bunsch, 2012), photogrammetric view planning is more challenging because the knowledge of a 3D surface is not immediately available after acquiring a single image, but instead needs to be computed by adding it to previous images and analyzing the resulting state.

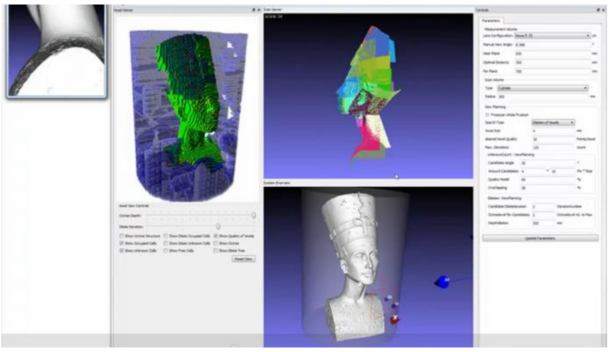


**Figure 5:** CultArm3D next-best-view planning for autonomous scanning of arbitrary objects.

### 3.3. Results and evaluation

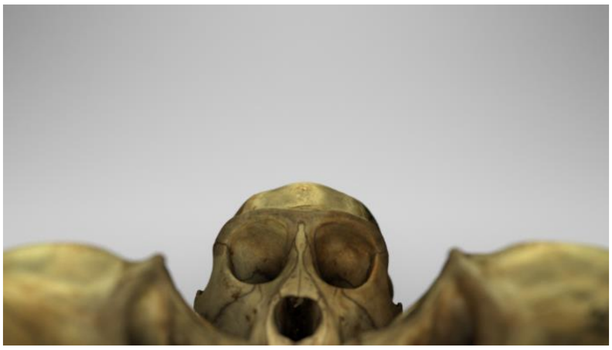
The entire scanning process of one object takes less than ten minutes on average, depending on its complexity to collect all necessary pictures for an offline 3D photogrammetric reconstruction. At any given moment, two artefacts are scanned in parallel. The resolution of the final models is around 200 - 300 µm. Due to the design of the CultArc3D optical material properties can already be captured to acquire the appearance model of an artefact but are not yet processed. The model can subsequently be linked to other 3D data as well as to provenance information such as the artefact’s period of origin or artist. For more information, see section “3D centered annotation and visualization” of this article.

During development several user tests, e.g. with partner museums in Germany, were performed to evaluate the acquisition procedure under real museum conditions. A selection of objects differing in size, quality and material properties were digitized at prestigious institutions such as the Liebieghaus sculpture collection (*Liebieghaus Skulpturensammlung*) in Frankfurt, the Museum of Natural History/Leibniz Institute for Evolution and Biodiversity Science (*Museum für Naturkunde/Leibniz-Institut für Evolutions- und Biodiversitätsforschung*) in Berlin (see Figs. 6 and 7) and at the National Museums in Berlin, Prussian Cultural Heritage (*Staatliche Museen zu Berlin*, *Preußischer Kulturbesitz*). CultLab3D demonstrated that it is feasible to achieve good results at an average throughput of 10 minutes per bust-sized object for the acquisition of its geometry and texture while computing the 3D reconstruction offline, in most cases without any additional need for manual intervention.

(a)

(b)

**Figure 6:** Result of scanning a stuffed chameleon with the CultArm3D: a) Rendering of 3D model with texture; b) No texture applied to the 3D model to reveal the geometry details. © Fraunhofer IGD.



(a)

(b)

**Figure 7:** Result of scanning a gorilla skull with the CultArm3D: a) Rendering of 3D model with texture; b) No texture applied to the 3D model to reveal the geometry details. © Fraunhofer IGD.

Photogrammetric methods are difficult to evaluate since accuracy depends on the combination of the sensor resolution(s) of the camera(s), the method of combination of sensors for geometry computation, size and distance of the object surface from the sensor, surface structure and materials affecting reflectivity and contrast, just to name a few. Also the parameters of photogrammetric reconstruction, especially for Multi-view Stereo, such as the number of feature points considered during reconstruction, have a significant impact on density of the resulting 3D model and quality. Feature points are positions on the object surface that can be uniquely identified in different camera perspectives. A theoretic estimate on maximum accuracy can be given based on the above parameters. For CultLab3D we have done a different evaluation taking an independent high-precision geometry scanner as a reference.

The accuracy of the intermediate and final results of the CultLab3D photogrammetric reconstruction pipeline was evaluated in comparison to a high-precision scan from a structured-light phase-shifting scanner (Polymetric PT-M4, measurement field 265 mm x 256 mm, point spacing 130 micron, depth resolution 16 micron) that serves as the ground truth mesh (GTM). The point cloud from the photogrammetric reconstruction was registered with the GTM using the Iterative Closest Points (ICP) method. For comparison between the structured-light scan and the photogrammetry results of the two CultLab3D scanning stations the method by S.M. Seitz et al. (Seitz, Curless, Diebel, Scharstein, & Szeliski, 2006) was applied with an according threshold setting of 90%. The obtained accuracy value represents the maximum distance of the 90% best-fitted points. An accuracy value of 1 mm, e.g., means that 90% of the points are within 1 mm of the GTM. While the accuracy of the first quick scan using only the CultArc3D station was at 1.33 mm, the accuracy of the final combined scan involving the CultArm3D improved to 0.21 mm (see Fig. 8), underlining that the achievable accuracy of CultLab3D approaches the 200 micron mark. This also shows that the quality of the 3D model increases as the artefact passes the two consecutive scanning stations CultArc3D and CultArm3D. While the first station, CultArc3D, provides a first quick result, serving as basis for next-best-view planning for the second station, CultArm3D applies a slower but more focused image acquisition which allows to enhance especially the poorly textured areas, e.g., at the neck and chin. The combination and intelligent interplay of both ultimately leads to a high efficiency and at the same time high-quality results.

## 4. 3D centered annotation and visualization

New and improved technologies for mass digitization lead to a rapid increase of digital surrogates. Once they are available, an appropriate storage solution and a complete digital library service handling, e.g. for indexing, retrieval and permission management, is needed. In this context, an object and metadata repository infrastructure for annotation of artifacts is needed.

Existing and applied standards like LIDO, which combines elements of CIDOC CRM and *Museumdat* for the minimum description of digital data used in virtual exhibition environments, will be taken into account. Current content management systems used in the museum domain are very text-centric, such as Adlib Museum, MuseumPlus or Museumindex (Collections Trust, 2016). They provide support for a variety of metadata schemata such as CIDOC CRM, LIDO, METS and a range of document, image and media formats.

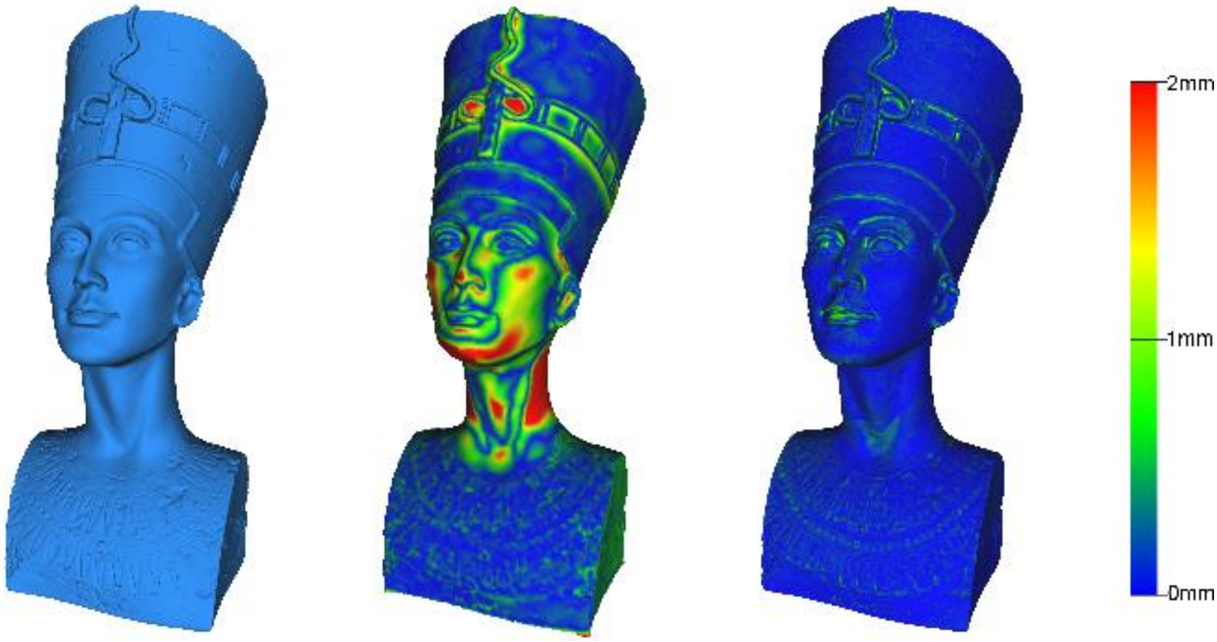



**Figure 8**: Left: ground truth model. Middle: comparison with the intermediate scan from CultArc3D. Right: comparison with the final scan as a combined result of CultArc3D and CultArm3D captures. © Fraunhofer IGD.

However, native support for 3D formats to annotate, store and display virtual 3D models is non-existent, which is even truer for 3D visualization and analysis. The most used workaround is to only store 3D data and then link it to external tools to open, visualize and work with the data.

There have been some projects focusing on 3D centered interaction such as 3DSA (3DSA, 2016) from the University of Queensland featuring direct annotation, metadata connection and measurements on the object's surface. Also some scanner companies such as Artec have started to include basic annotation functionality to work with 3D models in their products. Other examples include the Smithsonian X 3D Explorer, implemented in collaboration with Autodesk (Smithsonian, 2016). The web application uses proprietary technology to showcase items on the web in 3D but does not integrate it into their database backend. It allows users to explore, measure and light objects and present narrative stories centered on the 3D artefact. On the end-user side, the tool only requires an internet connection, can be run on any platform featuring a recent web browser and supports a variety of metadata formats such as the one used by Europe's digital library portal Europeana.

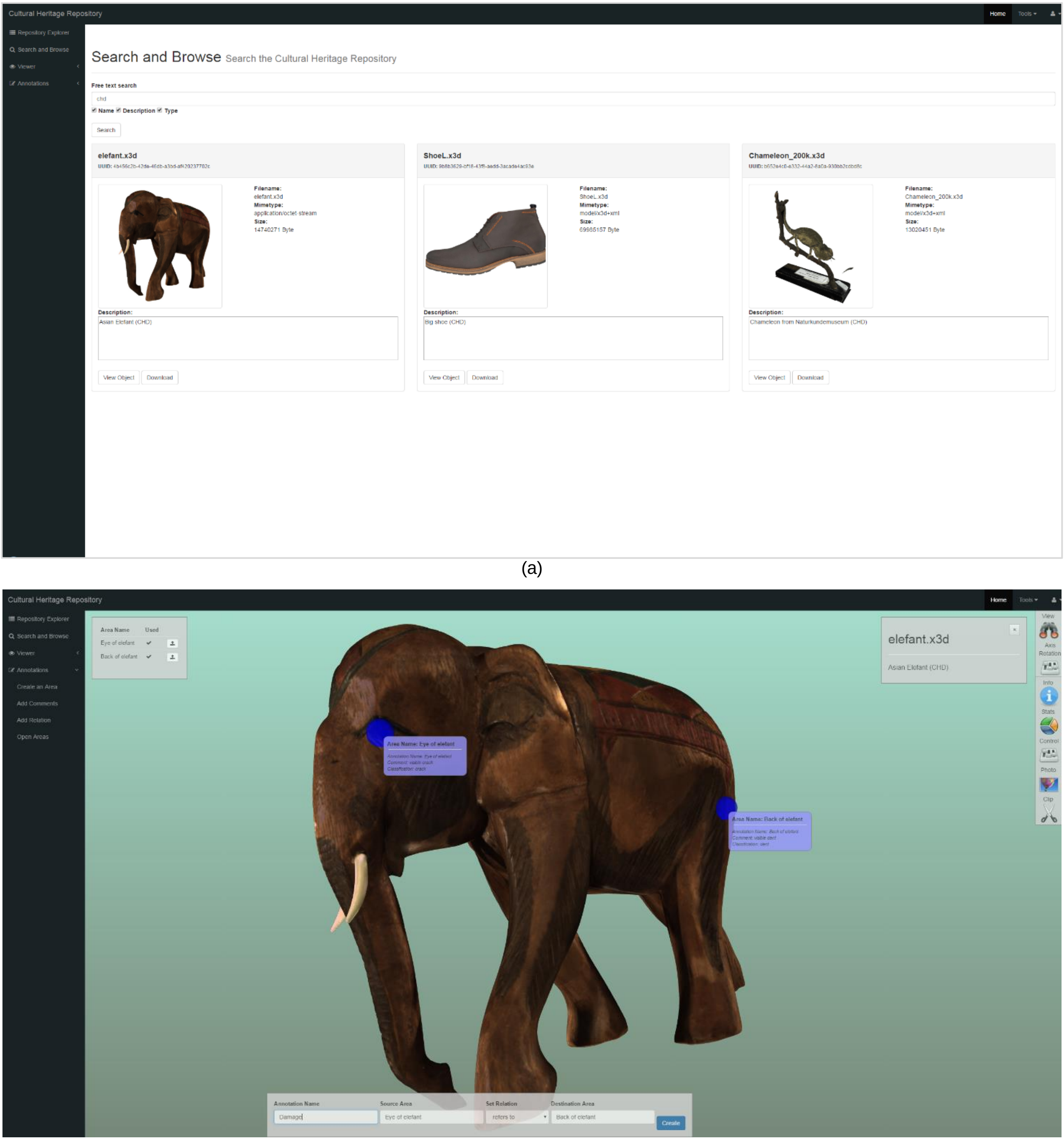
CultLab3D proposes a paradigm shift by developing a 3D centered web-based annotation tool called the Integrated Viewer Browser (IVB, frontend) allowing to directly create annotations on the 3D object surface by using drag and drop. It is web-based, has a user-friendly interface and runs on any platform (stationary workstations and mobile devices). Knowledge on restoration processes, art historical and cultural background or on provenance data can thus be made available through the use of semantic technologies. The backend consists of a CIDOC-CRM and CRMdig conform metadata repository using Fedora Commons as well as of object data repositories. The 3D annotation system is based on work done in the EU project 3D-COFORM (Echavarria et al., 2012) but has been completely rewritten and brought to the Web relying on the X3D standard to display 3D content without need for further plugins in all HTML5 compatible browsers (see Fig. 9).

## 5. Summary and outlook

CultLab3D contributes significantly to a broader access to cultural heritage for research and the public. By providing a flexible and efficient 3D scanning and annotation system that meets the specific needs of cultural heritage institutions, it fosters an innovative approach to documentation and preservation. 3D mass scanning can help to make cultural heritage more widely available, to secure it for future generations and to reduce the wear and tear on objects by working with replicas instead of the precious original, e.g. in research settings.

The fact that merely a small amount of artefacts in collecting institutions is made publicly available indicates a need for improving accessibility to heritage information in accordance with modern requirements (Keene, 2008). Millions of cultural resources await documentation, classification, and in many cases (re)discovery in storage. For example, the collection of the National Museums in Berlin, Prussian Cultural Heritage (German: *Staatliche Museen zu Berlin, Preußischer Kulturbesitz*) consists of more than six million objects with about 120000 new additions per year, making it necessary to index historic material on a large scale.

While CultLab3D has only focused on capturing surface data under daylight conditions so far, it should be understood as the foundational cornerstone of a larger development and paradigm shift much like the introduction of the assembly line in the automotive industry reducing costs and making cars affordable and accessible to a wider audience. Future development will include multi-spectral lighting. For example, infra-red light can help to visualize the conservation state of an object while ultra-violet light helps to visualize the marks of a chisel on a wooden statue and therefore yield valuable information on carving techniques employed by the original artist.




(a)

(b)

**Figure 9**: Web-based 3D-centered annotation browser: Query interface and annotation tool: a) Search and Browse; b) 3D visualization of 3D model and 3D centered annotation. © Fraunhofer IGD.

CultLab3D is currently generating surface models but in the long run it is supposed to accomplish consolidated 3D models fusing data from a variety of capture sources. Additional scanning modules may add volumetric data using ultra-sound or CT technology or even contribute with information about the inner stability of an artefact using mass spectroscopy. All these technologies will lead to consolidated 3D representations of heritage objects at reasonable cost, by using the modular CultLab3D digitization approach. Decimated variants of the final results can then be used for a variety of purposes, ranging from scientific work to commercial purposes, fostering new levels of information accessibility and revenue streams for cultural heritage institutions to preserve our past for future generations to come.

First important initial steps have been taken in this direction within the pilot project Fraunhofer innovations for cultural heritage (Fraunhofer Innovations, 2016). The aim is to combine novel technologies developed by the Fraunhofer IGD for the first time in order to create consolidated 3D models from surface and volumetric scanning data. The technologies applied come from the following four areas:

- 3D digitization (e.g. *CultLab3D*),
- confocal microscopy,

- terahertz technology and
- mobile ultrasonic tomography.

Hence, improved sculpture monitoring is rendered feasible. 3D models also allow for a profound damage analysis for further works requiring knowledge of the artefact's condition and thereby contribute significantly to decisions regarding conservation. Optical, electromagnetic, and acoustic methods are combined for the first time in order to extensively analyze the condition of sculptures in the Dresden State Sculpture Collection, Germany (*Staatliche Skulpturensammlung Dresden*).

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