A FLEXIBLE WORKFLOW FOR MULTIMODAL 3D IMAGING OF VAULTED PAINTED CEILINGS IN HIGH DETAIL

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ABSTRACT:

3D imaging is an increasingly common tool for the investigation of cultural heritage. Painted ceilings offer particular challenges as the art historical requirements necessitate highly detailed and accurate capture of colour textures with sub-millimetre resolution, even of large areas of 100s of square metres, situated in a wide variety of building environments. Geometrical information is also required to represent fully the three-dimensional nature of these sculpted and vaulted ceilings, again at the resolution necessary for both documentation and use by cultural heritage professionals including conservators, restorers, building researchers, architects and art historians. This paper describes a multi-modal campaign of 3D digitisation of three very different sites undertaken as part of the Franco-German Plafond 3D project. We introduce a flexible and adaptable methodology that allows the detailed imaging of large interiors and ceiling paintings in a short period of time and with varying levels of access.

1. INTRODUCTION

Photogrammetry has a long history of use in examining painted surfaces and painted ceilings, though in the past this has often involved specialist equipment and workflows, and the imaging of small areas (MacDonald et al., 2014). The requirements of this project necessitate the 3D digitisation of large rooms, and specifically painted, vaulted fresco'd ceilings in a resolution high enough for both comprehensive documentation and to facilitate research questions in art history, conservation/restoration, architectural history and building research.

The 'al fresco' ('in fresh') technique involves painting onto wet plaster, often prepared with stencils or other forms of drawing. After drying, pigments become an integral part of the surface. The technique is widespread throughout Europe and elsewhere, and was particularly prevalent in the baroque era. Both art and architectural historians are interested in discovering traces of the artists' workings on these frescoed surfaces.

Frescos, and in particular ceilings, offer particular challenges in 3D imaging due to the difficulty of attaching targets and control points to painted surfaces. Thus, the project aims to combine 3D laser scanning and photogrammetry to ensure accurate scaling and geometrical accuracy.

This paper is concerned with the German side of the Plafond 3D project, tasked with digitising three 17th and 18th century baroque buildings (see 1.1). Though multiple objects areas were captured with a variety of imaging methods, this paper will be concerned with the three primary outputs, (1) a 3D model of the banqueting hall in Dresden's Palais im Grossen Garten; (2) the Festsaal (ballroom) ceiling painting in the Ansbach Residenz and (3) the Spiegelsaal (mirror hall) ceiling in Schloss Rheinsberg.

1.1 The Plafond 3D project

The three year international and interdisciplinary Plafond 3D project is co-funded by two national research associations, the Deutsche Forschungsgemeinschaft (DFG) and the Agence Nationale de Recherche (ANR). It is concerned with the "historical, cultural, formal, and technical phenomenon" of 17th and 18th century French and German painted, vaulted ceilings (Plafond3D, 2022), (Hess, Burioni and Bonfait., 2022). The project has multiple aims. As well as systematising and improving interoperability of 20 years of French and German research, creating an online directory and conducting a detailed 'microhistory' art-historical investigation of French and German profane ceiling paintings, the project has particular interest in ceiling paintings as a three-dimensional medium. As such 3D digitisation and 3D visualisations will be fundamental (Burioni, 2020). Six sites (three each in France and Germany) will be digitised in 3D with the outputs disseminated for use in art historical, restoration-conservation and architectural research. Public engagement is another key focus of the project with the 3D visualisations opening up various opportunities for outreach to a broader audience, including a virtual exhibition to be created at the end of the project, virtual tours of destroyed buildings, and VR (Virtual Reality) and AR (Augmented Reality) applications to engage a lay audience in these heritage objects.

All raw data, text, images and 3D models will be made available as open data and licensed under Creative Commons licenses, and the metadata released as standards-compliant Linked Open Data. The models will be linked to the research blog of the project (plafond3d.org, 2023) and made accessible in public open data repositories. The German-French Plafond 3D project is linked to the Bavarian Academy of Sciences and Humanities' long-term research project, Corpus of Baroque Ceiling Paintings in Germany (CbDD). The results achieved in Plafond 3D will be integrated into the database (CbDD website, 2023).

1.2 State of the art

Other projects concerned with high resolution 3D recording of similar cultural heritage objects and typologies have approached the problem with combinations of laser scanning and/or photogrammetry (Rahrig, 2020), (Guarneri et al., 2019). Specific questions, such as necessary resolution for answering art-historical questions were addressed in (Valente et al., 2019), and the creation and provision of 3D models for conservation/restoration purposes in (Percy et al., 2013). Particular difficulties and workflows for fresco'd ceilings and the combination of laser scanning and photogrammetry to acquire accurate scaling are in (Bruno et al., 2022).

1.3 The case studies

1.3.1 Palais im Grossen Garten, Dresden: Construction of The Palais im Grossen Garten (Grand Garden Palace), Saxony's earliest Baroque building, was begun in 1679. The palace was designed by the Saxonian court architects Wolf Caspar von Klengel and Johann Georg Starcke, and the central two-story banqueting hall originally featured a Samuel Bottschild ceiling painting. Tragically this, along with much of the original structure, was heavily damaged in the fire-bombing of Dresden in 1945 (CbDD et al., 2022) and parts of the still extant interior stucco decoration were lost due to neglect after the war. The building was stabilised in the 1960s, with a new vaulted concrete ceiling completed in the 1990s. The building, particularly the central banqueting hall is currently used for exhibitions, music recitals and private-hire.
Through the loss of the original building fabric is an undoubted tragedy, the current state of the Palais and banqueting hall, with its areas of exposed brickwork, does give a unique insight into architectural and building techniques of the baroque period. This offers many opportunities for building research (“Bauforschung” / building archaeology) and cultural heritage conservation (Pattee et al., 2023). The requirements of the imaging in Dresden included a detailed 3D model of the banqueting hall with sufficient texture detail to be able to identify individual building elements (for example single bricks). The classical methods of drafting can be sped up and helped by the use of orthophotographs from 3D imaging, see section 2.1.

1.3.2 Residenz Ansbach, Bavaria: The Residence of Ansbach, constructed during the 16th and 17th centuries was originally the seat of the Margrave of Brandenburg-Ansbach and is currently the administrative seat of the government of Middle Franconia. The vaulted Festsaal (Ballroom/Great Hall), approximately 254m^2 is decorated with a fresco by the Italian rococo artist Carlo Carlone (1686-1775), one of the most successful itinerant workshops for ceiling paintings in the eighteenth century, active in Italy and Germany. The ceiling is currently (2023-2026) undergoing major restoration work by the Bayerische Schlösserverwaltung (Bavarian Palace Administration), and thus a scaffolding platform covers the entire area of the hall, with an approximate 2m clearance to the ceiling (fig 1). This provides a unique opportunity to scan the fresco in high resolution from close range and thus to gain new insights into the working procedures of one of the most important fresco workshops of the eighteenth-century.
The art historical and conservation requirements included a model of the entire ceiling with the ability to see features in the order of 1 mm, as well as imaging of two further areas in sub-mm resolution to investigate Carlone's fresco technique.

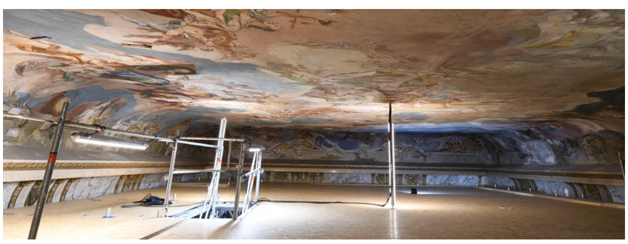

Figure 1. Ansbach ceiling with scaffolding platform

1.3.3 Schloss Rheinsberg: The Schloss Rheinsberg (Rheinsberg Palace) is part of the Prussian Palaces and Gardens Foundation Berlin-Brandenburg (SPSG) and was the home of crown prince Frederick (later Frederick II, also Frederick the Great) from 1736 until his accession in 1740. It is decorated with the first known ceiling paintings by French artist Antoine Pesne (1683-1757), who until this point had painted only on canvas (CbDD et al., 2021). In contrast to Pesne's later ceiling paintings for Frederick II, which, with the exception of Schloss Sanssouci, were destroyed by bombing during WW2 and later by the GDR government, the decoration of Schloss Rheinsberg is largely intact and well preserved. Thus the particular style of his oil on plaster ceiling painting can be studied in its earliest phase only in Rheinsberg. The excellent documentation and preservation of Schloss Rheinsberg makes it possible to study how an interior decoration was conceived and executed by a team including Georg Wenzeslaus von Knobelsdorff, Antoine Pesne, Augustin Dubuisson, an anonymous stucco artist and boiserie, and Johann Carl Scheffler, who was responsible for the doors.
Five ceilings were imaged: the knights hall (Rittersaal) featuring a painting of Venus and Mars, three smaller rooms - an antechamber with clouds and putti, and two tower rooms with paintings of Ganymede and Hebe and Minerva - and the primary focus of this project, the Spiegelsaal with its fresco of the Aurora.

2. METHODOLOGIES

2.1 Dresden

2.1.1 Data capture

The 3D imaging/scanning campaign in Dresden took place over two days in October 2021, and involved two imaging specialists from the University of Bamberg with a technician and two student helpers, alongside input and assistance from art historians from LMU in Munich. Whilst multiple areas (including the entire building, inside and out) were imaged, the focus in the Palais was primarily the remains of the 1st floor banqueting hall. This large space (≈ 278m^2) is divided from two rooms at either end by three large arches, and is flanked by two small vestibules leading to the gardens. Some of the original (albeit damaged) stucco remains on the walls, though the ceiling and floor are entirely reconstructed. One corner has been partially restored using pre-war photographs.

Three different 3D scanning technologies were used in this building. The entire building, both interior and exterior, was scanned using the SLAM method (simultaneous localisation and mapping) with a handheld Geoslam Zeb Horizon mobile laser scanner, which can capture 300,000 colourised points per second with an accuracy of up to 6mm at 100m (Geoslam, 2021). The interior, both ground and first floors, was also scanned with a Leica BLK360 terrestrial laser scanner (TLS, capturing 360,000 points/second, range up to 45m with an accuracy of 4mm at 10m (Leica Geosystems, 2023)). An HDR camera system, integrated into the scanner, captures a spherical image for each scan. Some areas (the two alcoves with surviving ceiling paintings on the ground floor, and the surviving stucco in the banqueting hall were also scanned in more detail with a Faro focus TLS (phase shift scanner, capturing up to 1 million pps with up to 2mm accuracy at 10m range (Faro, 2023).

Figure 2. Multi-camera setup for Dresden

Four small objects in the banqueting hall (between approx. two and four m^2) were scanned with an Artec Eva structured light scanner (0.1 mm acc-uracy with a resolution of ≈0.2 mm) (Artec3D, 2020). These areas, selected by colleagues from LMU, are of both art-historical and arch-itectural interest. Some feature original stucco, and one of the columns has damage that reveals construction techniques. As well as two ground floor alcoves with surviving ceiling paintings, photogrammetry was used to capture the entire 1st floor, including the focus of the campaign, the banqueting hall. In order to expedite the capture, a multi-camera rig was used, featuring four Nikon D340 cameras mounted on a modified golf trolley (fig 2). The cameras were fitted with Nikkor DX 18-55mm lenses, set to 18mm. Images were taken with ISO 100, aperture F/4 and exposures between 1/80 and 1/10. Originally it was planned to tether the cameras to a laptop and trigger them simultaneously using a python script, however, the data transfer time was prohibitively slow, and instead the four cameras were triggered individually using a remote control and the images stored locally. In future, it should be possible to adjust the software to trigger the cameras simultaneously. Having the multi-angle set-up drastically decreased the time required for capture, with approximately four hours needed to take the 1200 images required to image the entire floor. Figure 3 shows the layout and the camera network acquired.

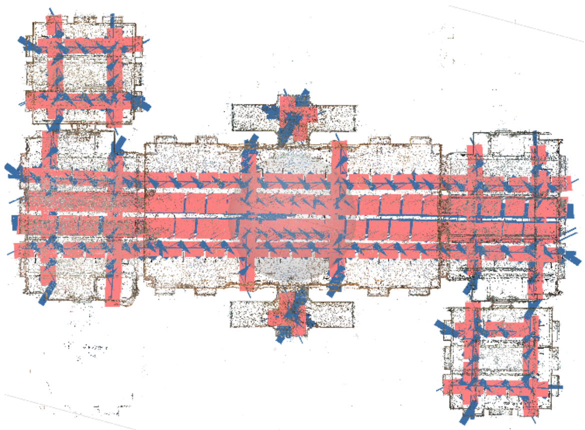

Figure 3: Palace 1st floor layout in Dresden Palais with photogrammetric network

2.2.2 Processing: The laser scans from the BLK scanner were aligned and processed in Cyclone Register and exported as E57 point clouds. These were imported into CloudCompare where the point clouds were cleaned to remove extraneous details and noise such as the four glass chandeliers and figures and equipment. The cloud was filtered with a point-spacing of 3mm to create a cloud of ≈72 million points from which a 30 million triangle mesh was produced. This mesh was then further processed in Geomagic Wrap (2021), with repairs made to areas such as the windows where scanning was difficult, and minor issues with the mesh fixed using the mesh doctor algorithm. Finally, the mesh was iteratively decimated and exported at various sizes (fig 4).Raw image processing was carried out in Adobe Lightroom. Imaging was conducted on a sunny day, and thus while some areas were brightly lit via the large windows, some (for example the small

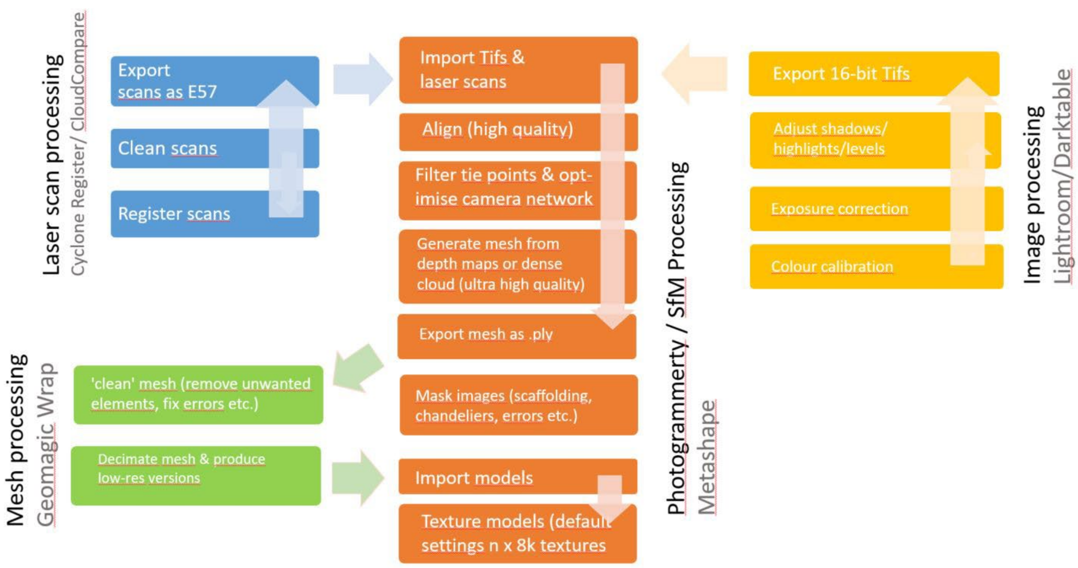

Figure 4. Generalised processing workflow for Plafond3D

side rooms) were extremely dark. Therefore highlights and shadows were processed to reveal details in under and over-exposed areas. The images were exported as 16-bit TIF files.

The SfM processing was conducted in Agisoft Metashape (versions 1.7 & 1.8). The TIF images were aligned to create a model of the first floor with parameters Accuracy High, a 40,000 keypoint limit and 4,000 tie point limit. The initial sparse point cloud of 543,201 tie points had reprojection errors of max 34.41 pix and RMS of 0.69. After an iterative process of filtering the point cloud via reconstruction uncertainty, projection accuracy and finally reprojection error, the point cloud was reduced to 104,883 tie points with a max error of 1.83 pix and RMS of 0.29.

For the model of the banqueting hall, the processed and edited laser scan mesh was imported into Agisoft Metashape. Coordinates for the chequerboard targets were exported from the laser scan data, and these targets identified and marked on the photos. The 3D coordinates for the markers were manually entered in Agisoft Metashape, aligning the mesh with the camera network. The images were masked to remove the chandeliers, and the model then textured, generating 20x8k images. This process was then repeated with a lower resolution mesh (approx. 1m triangles and 4x8k texture), with the model exported as a *.glb* file for web publication in online 3D repositories.

(NB: We have updated the workflow to now process the laser scans with the photographs in the alignment stage of the photogrammetry. The Dresden model has since been reprocessed using this new workflow, and while the photogrammetric mesh shows considerably more detail in some areas, the features of interest (see 3.1) have approximately the same level of detail.)

2.2 Ansbach

2.2.1 Data capture of the Festsaal: After an initial exploratory visit in February 2022 with membersof the Bayerische Schlösserverwaltung (Bavarian Palace authorities) and art historian colleagues from LMU, imaging was conducted over the course of two weekends in May and June 2022.

On the first imaging campaign, the scaffolding platform only covered approximately 2/3rds of the room, so capturing the entire ceiling was impossible. However, the entire Festsaalwas scanned with the BLK laser scanner, both above (ca. 12 positions) and below the platform (ca. 30 positions). The scaff-olding also allowed access to the detailed stucco work above the doors (‘supraporte’) and below the windows, and two areas were scanned in detail with the Artec Eva SLS. Areas of this stucco were also captured in more detail with close range photogrammetry, in order to map damages and reveal manufacturing tech-niques. In this case evidence of the use of pre-fabricated stucco in combination with on-site stucco was visible, partly damaged with cracks and surface loss (see Fig. 5).

Figure 5. Supraporte stucco: top - untextured SL scan; bottom - photogrammetric model

Two areas of the ceiling were imaged in high detail using photogrammetry. An area of approx. 1m^2 featuring a river God (fig. 6), and a slightly larger area (≈3.5m^2) which includes an oil portrait of the Marg-rave of Ansbach, also by Carlone, inserted into the fresco. The insertion of an oil painting into a fresco is highly unusual (Mauss et al; 2022). These areas were selected by the art historians and conservators of the Bayerische Schlösser-verwatlung, as they both featured marks indicating where the artist had prepared the wet plaster before painting. In both cases, the area was illuminated with a pair of Elinchrom D-Lite soft-boxes, and photographed with a Nikon D850 mounted on a tripod with a full-frame 105mm lens. Scale was provided by scale bars (Mallison, 2023) mounted on tripods close to the ceiling, and exposure and colour calibration provided by an X-Rite colour checker (xRite, 2023).

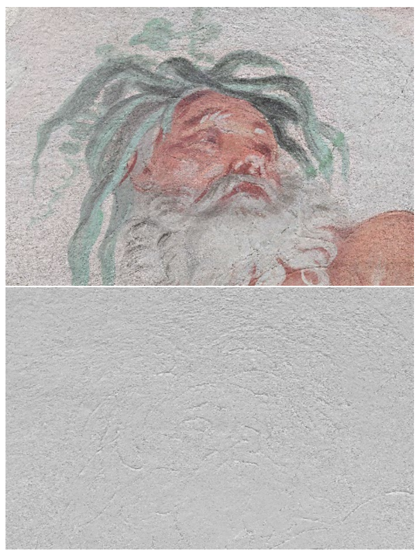

Figure 6. River God detail; coloured & uncoloured point cloud

For the first area featuring the river God, the camera was situated approx. 45 cm from the ceiling and 504 photos were taken with an overlap of 80% and settings of exposure 1/200, f/13 and ISO 100. This gave a depth of field of around 1.8 cm, which was just enough for the largely flat ceiling. The FoV (field of view) was approximately 154x102 mm giving a GSD (Ground Sampling Distance) of .018 mm (18 µm), more than sufficient resolution to investigate faint incisions (Valente et al., 2019).

The second area was captured in 239 images, with settings of 1/200, f/14 and ISO 100 and from a distance of approx. 1.6 m, giving a FoV of 550x362mm and a GSD of .07 mm (70 µm).

On the second visit, the platform extended across the entire hall, allowing the complete ceiling to be imaged. In addition, further BLK scans were made, including in the roof space above the ceiling. Imaging the ceiling presented several interesting challenges. With no natural light, the images had to be illuminated artificially, and this, combined with the 2m clearance between the platform and ceiling severely restricted the potential field of view for imaging. Thus, between the visits in May and June, a new methodology was developed to enable the entire ceiling to be captured in the limited time available.

Initially, the entire area above the scaffolding was captured with a wide-angle lens and a combination of the available illumination (three fluorescent tubes situated in one corner of the ceiling) and several Scangrip Nova R LED spotlights. The D850 full-frame camera was used with a 12-24 mm lens, and a ring of 30 images at 12mm focal length were taken of the entire ceiling area.

For the high detail recording of the ceiling painting, the D850 was used with a Godox Witstro AR400 ring flash. The widest angle lens that was available and could be used in this configuration was an 18mm DX lens, so the camera was operated in cropped-sensor mode. The camera was mounted approx. 1.5m from the ceiling, giving a field of view of approximately 200x133cm and a GSD of approx. 0.35mm (350µm). Thus, in order to capture the required number of images (approx. 1400 to cover the full 220m^2 with an 80% overlap) a semi-automated imaging solution was developed.

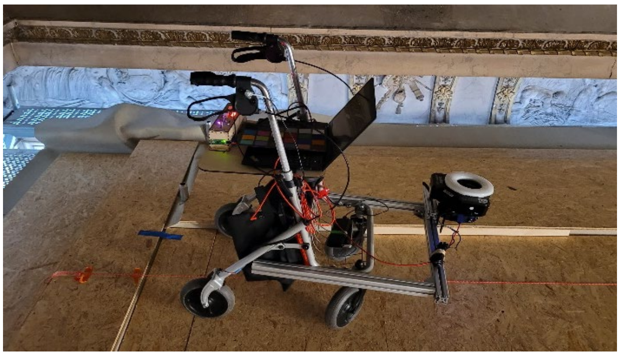

Figure 7. CHAPI setup for Ansbach imaging

The group at Bamberg university designed a purpose- built tool, CHAPI (Cultural Heritage Automatic Photogrammetric Imaging) (Hindmarch et al, 2023), a mobile platform built on a wheeled walking frame (fig 7). Sensors linked to a microcontroller allow the camera, tethered to a laptop running Nikon Capture One software (Nikon Inc., 2023), to be triggered automatically at a specified distance (in this case every 30cm). This allowed the entire ceiling to be imaged in just over 5 hours (not including pauses to recharge the laptop and allow the overheating flash to cool). Settings used were 1/200 exposure, F/11 and ISO 100.

In addition to the 1400 orthogonal images of the ceiling, two further rings of the vaulting, at 45° (122 images) and 90° (161) were taken with CHAPI, as well as some extra images in areas around obstructions such as the scaffolding.

2.2.2 Processing

2.2.2.1 Detail areas

The 16-bit images were colour calibrated in the open source Darktable image editing software (Darktable, 2023) and exported as 16-bit *Tif*s. The *Tif* images were aligned in Metashape at high accuracy with key and tie point limits of 100,000 and 10,000 respectively. The sparse point cloud was filtered to improve accuracy and a dense point cloud generated at Ultra high quality (Table 1). Work is ongoing to determine what size mesh can be generated that is both usable and sufficiently detailed to answer research questions.

	Tie points (after filtering)	Reprojection error RMS	MAX	Dense point cloud
Area 1	71,931	0.18	0.69	1.6 billion points
Area 2	92,758	0.21	1.5	861 million points

Table 1. Alignment statistics for detailed area of the ceiling

2.2.2.2 Entire ceiling

Data was processed according to the workflow in fig. 4, resulting in a sparse point cloud of 260k points with reprojection errors of RMS .25 and max 1.3, a dense point cloud of 2.4 billion points and a mesh with 301 million triangles

Due to the discrepancy between the camera's field of view and the coverage of the flash, all images were masked with a simple circle, so that only the illuminated pixels would be used for texturing (fig. 8). The wide-angle images were disabled, and 20x8k textures generated.

Due to issues with lighting the vaulting, particularly with the images taken at 45° (the uneven distance from flash to surface leading to major variations in illumination), there were noticeable colour discrepancies around the sides of the model. An attempt to fix this was made by manually adjusting the exposure of the images taken at 45 and 90°, and masking the subsequent over-exposed areas. This process resulted in a much improved output, though further work is needed, as there are still some subtle but noticeable colour issues at the interface of the vaulting and ceiling.

2.3 Rheinsberg

2.3.1 Data capture: The Palace in Rheinsberg was imaged by a team of three over two days. Taking advantage of our access to the site, the complete interior and surroundings of the palace were recorded with the GeoSlam Horizon. The five prioritised rooms and the rooms adjacent were scanned with the BLK360 to support the scaling of the photogrammetric recording and to facilitate the connection of the various interiors. Photogrammetry was conducted on the two large rooms (Rittersaal and Spiegelsaal, using CHAPI) and the three smaller rooms, all featuring ceiling paintings by Pesne.

Figure 8. Photo of Ansbach ceiling showing limited extent of the flash

The primary focus of the campaign in this instance was the Spiegelsaal. The room measures approximately 12.5 x 11m with a ceiling height of between 5.0 and 5.5m. It has three large windows on the east and west sides, interspersed with full-length mirrors. An initial capture of the entire room was made with the Nikon D850 and wide-angle (12 mm) lens consisting of 133 images (F/4, ISO 125, 1/10 exposure). For the high-resolution imaging of the ceiling, CHAPI was used with the D850 and a full-frame 105mm lens (F/11, ISO 125 and variable exposure).

827 images were taken with an 80% overlap. The distance to the ceiling was 4.5m and the field of view 150x100cm, giving a GSD of .185mm (185µm). Due to the available light being highly variable (a bright day with intermittent cloud cover), and changing dramatically even between individual photos, an exposure time of between 1/3 and 1 seconds was used and adjusted manually according to light conditions. Due to the long exposure time, CHAPI was used in semi-automatic mode, with the distance travelled measured automatically but the camera triggered manually. To ensure all areas of the painting would be captured after masking, a further set of four rings (67 images) were taken at a slight angle around each of the chandeliers (at f/16 to give a greater depth of field). Another set of 307 images were taken of the vaulting, with a 50mm lens (F/11, ISO 125) at 45°, as well as some extra images of the stucco on the doors and around the mantelpieces.

2.3.2 Processing: Processing, according to the workflow in fig. 4, is ongoing, and a model of just the ceiling and vaulting has been produced with a sparse point cloud of 463k points and repro. errors of RMS 0.36 and max 2.3 pix. A 310 m triangle mesh was generated from the depth maps and textured (20 x 8k textures) using just the 105 mm images, with masks manually generated for the chandeliers.

The ceiling texture shows some mottling, presumably due to differing exposure values in adjacent photos, so the images are being further processed to correct for the variable lighting.

3. OUTPUTS

All data, both processed models and raw data (images, raw scans etc) plus associated metadata will be archived on NAKALA and the Bamberg University Research data repository, and will be available via DOI as open data with CC licenses. Processed models of relevant objects will also be available through the Plafond 3D and the CdBD databases. The structured light and photogrammetric models will be uploaded as lower resolution models on the web via Sketchfab (sketchfab.com, 2023) and the open source 3D viewer Kompakkt.de (kompakkt.de, 2023). Where appropriate, these models will be linked and annotated, indicating interesting features from architectural, historical and art-historical viewpoints. Art historical research in connection with the digitised objects will be reflected on the project blog.

The high-resolution outputs prioritised specifically for the Plafond 3D project are detailed below.

3.1 Dresden

Alongside the four structured light models and two smaller photogrammetric models, the primary output of this project was the combined laser scan and photogrammetric model of the banqueting hall. The final output is a 25 million triangle mesh textured with 20x8k images.

As a means of answering the relevant research questions, a set of high-resolution detailed orthophotos of all four walls of the banqueting hall (fig. 9) were generated in CloudCompare by. These were used to manually identify (using Inkscape software) the individual stones and other building features including iron nails, roof-tiles and iron anchors. These provide a valuable resource for building and architectural research (Pattee et al, 2023).

The laser scan data, both the mobile mapping with Geoslam Horizon of the whole building and surroundings, and the terrestrial laser scans of the interior, will be made available to the city authorities. The laser scans can be used directly to extract floor plans or sections, or to be modelled in H-BIM (Heritage

Figure 9. Orthophotos of west wall of Dresden Festsaal extracted from 3D model (Pattee, 2023)

Building Information Modelling) as information for building management, and can serve as a planning tool for the frequent events and exhibitions held in this building. A virtual reconstruction of the banqueting hall, using pre-war photography to re-create the original ceiling painting will be made, and parametric modelling used to investigate architectural-historical questions involving the exact shape and height of the original ceiling.

Figure 10. Detail of the Ansbach ceiling model, top - without texture, showing stucco elements (top right), damage (bottom left) and artist's marks; bottom - the same area with texture

3.2 Ansbach

The two photogrammetric models of the small areas of the ceiling have proven interesting to art-historians, as the resolution of the models is more than adequate to identify faint scratches and features at the sub-mm level. Simply removing the colour and displaying the surface geometry, particularly when combined with raking light illumination reveals or enhances features that are difficult to see even when examining the ceiling in person from close range (fig. 6) (something that will no longer be possible once the scaffolding is removed). The capture resolution of 18 and 70 microns respectively is more than sufficient to answer questions regarding the artist's methods. We have since been approached to image further ceilings in this resolution in order to answer specific art-historical questions regarding attribution and methodology. It is true, however, that the ability to record in such high detail was afforded by the current restoration project and the presence of the scaffolding and platform. Whether ceilings can be imaged on a larger scale and from 'normal' distances of perhaps five or even 10 metres or more is an open question that requires further research.

The full size model with its lower GSD of 350 microns is still sufficiently detailed to see cracks and other damages, while the texture resolution is good enough to see sub-mm detail, for example individual brush strokes and minor damage (fig. 10). Already, elements of Carlone's working practices have been revealed by the high-resolution textured model and orthophotos.

Many colour discrepancies in the final texture that were initially believed to be artefacts of the imaging process actually turned out to be present in the painting itself, due in part to previous cleaning and restoration activities, and discolouration due to an unknown process that is linked to the wooden superstructure supporting the plastered ceiling. This will be further investigated in the future using existing damage-maps of the ceiling, laser scans of the roof area above the hall, and possibly in conjunction with data from the ceiling recorded with a thermal camera (T-IR).

We have generated orthophotos at various resolutions for the Bavarian palace administration, to aid in the conservation/ restoration project, and we will repeat the imaging process after the restoration project is complete to provide a detailed before-and-after record of the campaign.

3.3 Rheinsberg

As the ceilings by Antoine Pesne in Charlottenburg, the Stadtschloss in Potsdam and Berlin are lost because of bombing during WII and demolition by the GDR government the only extant ceiling paintings by the French painter can be studied in Rheinsberg and Sanssouci. It is here that the painter of small format gallery pictures was asked by his patron, crown-prince Frederick, to decorate the ceilings. Beginning with a tower room with a painting in oil on canvas of Minerva, then four further rooms (Rittersaal, Vestibule, Spiegelsaal, Bacchus-kabinet) in oil on plaster, prepared a decorative system that was subsequently applied to the other great projects of interior decoration in Frederick's reign in Schloss Charlottenburg, Stadtschloss Potsdam and Stadtschloss Berlin.

The high resolution model of the Spiegelsaal will be helpful to assess and understand rococo building processes, and the artist's last minute adjustments to the interior decoration. In a second step, the 3D model of the Spiegelsaal will be used for an experimental study of artificial and natural light in relation to the ceiling painting as well as acoustics and sound, as music played a central role in Frederick's court.

Figure 11. Top: Textured model of the ceiling (note the colour discrepancies due to variable exposure, which still needs to be corrected for); bottom: untextured detail

Processing of the data from Rheinsberg is ongoing, but already, as in Ansbach, it can be seen that the resolution of the 3D geometry is enough to see cracks and damages. The texture is of a high enough resolution to see sub-mm details, individual brushstrokes and details of the artists' techniques (fig. 11), demonstrating that it is possible to make high-resolution high-detail models of ceilings even at larger distances.

4. DISCUSSION

One year into a three-year project, processing the data collected at all three sites is still ongoing, and the continued refinement of processing workflows is very much a learning process. Methodologies for capturing the data changed and evolved over the project, and the development of CHAPI proved essential not only for capturing large image networks in a controlled manner, thereby improving the final outputs, but also enabling image acquisition in a short space of time. This is an important consideration when budgeting projects and also when access is strictly time-limited, as is often the case in cultural heritage sites that are open to the public. Instructions for building CHAPI, and its software will be released under a CC license to encourage others to iterate on and improve the design (Hindmarch et al, 2023).

The data processing workflow is also evolving, and we are currently investigating ways of better combining the laser scan and photogrammetric data, and analysing the results. Nevertheless, we have shown that photogrammetry, with and without the addition of TLS data, is an effective method for documenting entire ceiling paintings at high detail.

To fulfil the project's public engagement remit, multiple models, from structured light scans of small objects to entire rooms and buildings, will be made available via the web, on both the Sketchfab and Kompakkt.de online 3D viewers. Annotations by experts will give virtual visitors key insights into the history and iconography of these important and complex works of art. In the case of the Ansbach Festsaal ceiling, where the ceiling will be closed to the public for several years, the 3D models can be used to communicate to the public both the process, and necessity of, the conservation work being undertaken. We will eventually be able to show a complete 'before and after' picture of the restoration. Offline, both the high quality 3D models and the orthophotos of the ceiling have already proved their use in answering art historical questions, and will also be used as part of an upcoming interactive exhibition where we will collaborate with the Bavarian Palace administration in creating a novel method of reporting on conservation campaigns (2022-ca 2026). For example, the full resolution orthophoto can be printed at 300dpi to create a single four metre wide image of the ceiling painting, or even a life-size version at around 72dpi.

A key question for the project is how can 3D technologies and 3D data be used to facilitate and promote further research. One issue which we will investigate over the remaining two years of the project is how best to share data with researchers, academics and professionals in fields such as art-history and conservation. By their very nature, the full-resolution models created during the project can be prohibitively large, with point clouds of billions of points or meshes with 100s of millions of triangles. Even a single full-resolution orthophoto of the Ansbach ceiling is a 1.6 gigapixel image, with a file size of around 5 gigabytes and is therefore not currently openable in (for example) standard Windows image apps. While free software is available that can be used to view both the 3D models (CloudCompare, Meshlab) and large images (irfanview, Darktable), these are not normally used by non-specialists, are not particularly user-friendly, and still require powerful computing hardware to comfortably inspect the largest models.

Nevertheless, the free online viewers are still capable of displaying high-quality models. Even when the geometry must be reduced from 100s of millions to 100s of thousands of triangles, texture quality can still be sufficient to closely examine the paintings. Kompakkt.de, currently being developed at the University of Cologne's Department of Digital Humanities, is a particularly promising platform, offering tools to annotate and collaborate, allowing anyone with a web connection to both view and contribute to a 3D model. This could be used to, for example, map damages or indicate work in progress for restoration and conservation activities, or as a hub for a distributed research collaboration.

Just as important is finding ways of adapting our data to work within existing workflows and software, for example discovering the best compromise between data quality and usability. How far can data be decimated and still be able to answer research questions is an open question.

A key feature of both the project, as well as German national and federal policy is that all data generated by the project be provided as open access data (DFG, 2022). A single data set (for example a set of raw images or laser scans) can be 100s of gigabytes, so sharing is not a simple process. However, through the use of NAKALA and Bamberg University's research data repository, these data sets can be found and accessed via DOIs. This ensures that others can verify the fidelity of the data, process their own models and take advantage of new algorithms, methodologies and increased processing power that will be available in the future.

5. CONCLUSION

The 3D imaging and visualisation of ceiling paintings, particularly examples of baroque vaulted and sculpted ceilings, is important, as the three dimensional nature of the object is an integral part of both the composition and the viewer's experience. The third dimension is thus vital in interpreting the object as a work of art. However, ceilings vary enormously in dimension, environment and accessibility, each one offering its own set of challenges. Thus, a flexible methodology that can be adapted to new circumstances is necessary. We have shown that using photogrammetry and a relatively low-cost device such as CHAPI, a simple and flexible solution to the problems of capturing large painted ceilings can be tailored to new situations and enable the efficient creation of high quality outputs with demonstrable utility in a variety of uses-cases.

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REFERENCES

Artec3D. (2020). Artec EVA handheld scanner: Portable 3D Scanner for fast and accurate scanning. https://cdn.artec3d.com/pdf/Artec3D-Eva.pdf

Bruno, N., Mikolajewska, S., Roncella, R., & Zerbi, A. (2022). Integrated processing of photogrammetric and laser scanning data for frescoes restoration. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVI-2-W1-2022, 105–112. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-105-2022

Burioni, M. (2020). Deckenmalerei und virtuelle Realität. Montage, Illusionsbruch und mobile Betrachtung. Digitale Raumdarstellung: Barocke Deckenmalerei Und Virtual Reality, 58–77. https://doi.org/10.11588/ARTHISTORICUM.774.C10124

CbDD, Hertzig, S., Hoppe, S., Locher, H., & Burioni, M. (2022). Dresden, Palais im Neuen Garten. Corpus Der Barocken Deckenmalerei in Deutschland. http://www.deckenmalerei.eu/a12591d5-4edc-4c15-8033-e467e58c3f60

CbDD, Hoppe, S., Locher, H., & Burioni, M. (2021). Schloss Rheinsberg. Corpus Der Barocken Deckenmalerei in Deutschland. http://www.deckenmalerei.eu/6a9258aa-4c42-4542-a4aa-9b68d2a2b062

CbDD website: https://deckenmalerei.badw.de /datenbanken.html (accessed May 9, 2023)

Darktable. (2023). Darktable: Open source photography workflow application and raw developer. https://www.darktable.org/ (accessed May 9, 2023)

DFG. (2022). 12.15-Merkblatt und ergänzender Leitfaden—Digitalisierung und Erschliessung (Digitisation and Dissemination, FAIR rules). https://www.dfg.de/formulare/12_15/12_15_de.pdf

Faro. (2023). Faro Focus S350 tech sheet, https://www.faro.com/Resource-Library/Tech-Sheet/FARO-Focus-Core-Laser-Scanner (accessed May 9, 2023)

Geoslam. (2021). Geoslam Horizon Spec Sheet 2021. https://geoslam.com/wp-content/uploads/2021/03/ Horizon_Spec_Sheet.pdf (accessed May 9, 2023)

Guarneri, M., Ceccarelli, S., Ferri De Collibus, M., Francucci, M., & Ciaffi, M. (2019). Multi-wavelengths 3D laser scanning for pigment and structural studies on the frescoed ceiling. The triumph of divine providence. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2-W15, 549–554. https://doi.org/10.5194/isprs-archives-XLII-2-W15-549-2019

Hess, M., Burioni, M., & Bonfait, O. (2022). PLAFOND-3D: Eine Verflechtungsgeschichte der Deckenmalerei in Frankreich und Deutschland 1600-1800, | FIS Universität Bamberg. https://fis.uni-bamberg.de/cris/project/pj00633

Hindmarch, J., Hess, M., Groh, M., Burioni, M. (2023) A semi-automated methodology for 3D imaging of large vaulted ceiling paintings. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Florence 2023 (in press)

Kompakkt open source 3D web viewer: https://kompakkt.de/home (accessed May 9, 2023)

Leica Geosystems. (2023). Leica-BLK360—SpecSheet.pdf. https://leica-geosystems.com/-/media/files/leicageosystems/ products/datasheets/leica-blk360---specsheet.ashx

MacDonald, L., Hosseininaveh Ahmadabadian, A., & Robson, S. (2014). Photogrammetric Analysis of a Heritage Ceiling. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL–5, 379–383. https://doi.org/10.5194/isprsarchives-XL-5-379-2014

Mallison, H. (2023). Scale bars – Palaeo3D. http://palaeo3d.de/WP/?page_id=23 (accessed May 9, 2023)

Nikon Inc. (2023). Nikon Capture One Pro software. https://www.captureone.com/en (accessed May 9, 2023)

Pattee, A., Burioni, M., Hoppe, S., Hindmarch, J., & Hess, M. (2023). (In press) Historical Construction Research based upon 3D digital documentation of the Baroque Palais im Grossen Garten in Dresden. UHDL2023.

Percy, K., Hanley, C., Santana Quintero, M., Fai, S., Ouimet, C., Cancino, C., Rainer, L., & Villacorta-Santamato, L. (2013). Recording earthen architecture at the Peruvian Andes: The case of Kuno Tambo church's historic wall paintings. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, II-5-W1, 235–240. https://doi.org/10.5194/isprsannals-II-5-W1-235-2013

Plafond3D, Lett, M., Bonfait, O., Burioni, M., & Hess, M. (2022). PLAFOND-3D. A connected history of painted ceilings: France-Germany, 1600-1800.

Plafond3D project blog: https://plafond3d.hypotheses.org/ (accessed May 9, 2023)

Rahrig, M. (2020). Praxistaugliche Digitalisierung barocker Prunkräume. *Digitale Raumdarstellung: Barocke Deckenmalerei Und Virtual Reality*. https://doi.org/10.11588/ARTHISTORICUM.774.C10135

Sketchfab baroque ceiling collection: https://sketchfab.com/DigitalTechnologiesCH_Bamberg/collections/baroque-ceilings-cbdd-plafond-3d-f9148ab8845644ea9cff790b66378726

Valente, R., Barazzetti, L., Previtali, M., & Roncoroni, F. (2019). Considerations on the use of digital tools for documenting ancient wall graffiti. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2-W9*, 731–737. https://doi.org/10.5194/isprs-archives-XLII-2-W9-731-2019

xRite. (2023). *ColorChecker Classic*. https://www.xrite.com/categories/calibration-profiling/colorchecker-classic (accessed May 9, 2023)