Towards 3D Digitization in the GLAM (Galleries, Libraries, Archives, and Museums) Sector – Lessons Learned and Future Outlook

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Abstract: ***The European Cultural Heritage Strategy for the 21st century, within the Digital Agenda, one of the flagship initiatives of the Europe 2020 Strategy, has led to an increased demand for fast, efficient and faithful 3D digitization technologies for cultural heritage artefacts. 3D digitization has proven to be a promising approach to enable precise reconstructions of objects. Yet, unlike the digital acquisition of cultural goods in 2D which is widely used and automated today, 3D digitization often still requires significant manual intervention, time and money. To enable heritage institutions to make use of large scale, economic, and automated 3D digitization technologies, 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 technology for collections of three-dimensional objects. 3D scanning robots such as the CultArm3D-P are specifically designed to automate the entire 3D digitization process thus allowing to capture and archive objects on a large-scale and produce highly accurate photo-realistic representations. The unique setup allows to shorten the time needed for digitization from several hours to several minutes per artefact.***

Index Terms: ***photogrammetry, cultural heritage, 3D, digitization***

1. INTRODUCTION

IN this paper we present a workflow, from photogrammetric acquisition in challenging environments to representation of the acquired 3D models in different ways, such as online visualization and color 3D printed replicas. Central to our workflow is the CultArm3D-P, a fully automated color-calibrated 3D-scanner able to scan arbitrary objects at reproducible high resolution at the push of a button. Our work lays the foundation for a full color end-to-end reproduction of artifacts. Our workflow has successfully been applied to several digitization projects of which we present a few results, such as a project in collaboration with the Bavarian State Archaeological Collection in Munich at the "Roseninsel" (Rose Island), an island in Lake Starnberg (Bavaria) where originals had to be replaced by 3D printed replicas due to humidity.

In another project with the Reiss-Engelhorn Museums in Mannheim we present results of what to our knowledge is the first ever automated photogrammetry-based 3D digitization of very small golden artifacts from the island of JAVA in Indonesia at very high resolution using a polarization approach combined with focus stacking.

We conclude with results and an outlook on the end-to-end reproduction workflow leading to virtual replicas (online 3D visualization, virtual and augmented reality) and physical replicas (3D printed objects).

2. DIGITAL CULTURAL HERITAGE STRATEGY

The European Cultural Heritage Strategy for the 21st century should be geared towards the Digital Agenda, one of the flagship initiatives of the Europe 2020 Strategy, in order to further promote information and communications technologies (ICT) needed to preserve, enrich, and open up our cultural heritage and to ensure education and life-long training for the benefit of today's citizens and future generations.

Europe's cultural heritage is an "irreplaceable repository of knowledge and a valuable resource for economic growth, employment, and social cohesion" [1]. But despite its importance, cultural heritage is often at risk to be damaged and

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compromised in value, making innovative documentation and presentation methods increasingly important. This heightened relevance results from both the desire to provide better access to unique objects, e.g. to make museum collections more easily available to a wider audience or for research, and the looming threat of losing them due to disasters and other environmental influences. How fragile Europe's cultural heritage really is was made apparent recently by several natural and man-made disasters. Incidents like the fire at Notre Dame Cathedral in Paris, or - outside of Europe - the intentional destruction of the ancient Semitic city Palmyra, Syria, and the archaeological findings at the museum in Mosul, Iraq, underline the need for new methods of documentation and preservation and have led to a re-evaluation of the importance of high resolution facsimiles.

Digitization has proven to be a promising approach to create precise reconstructions of heritage objects for their digital preservation and virtual representation. Accordingly, EU Member States are called upon by the European Commission to increase their efforts for digital availability, online accessibility and digital preservation of their cultural heritage material. In 2011 already, the European Commission advised on the necessity of digitization and online accessibility of historic inventories as part of the Digital Agenda for Europe. Among other points the request for improved conditions underpinning large-scale digitization [2]. As one of the flagship initiatives of the Europe 2020 Strategy, the Digital Agenda further defined the preservation of cultural heritage in Europe as one of the predominant key areas in the context of promoting innovation, economic growth and progress through better use of ICT. Digitizing the Member States' cultural material and its long-term preservation is defined to be essential for access to culture and knowledge, to promote Europe's cultural diversity and to bring unprecedented economic opportunities.

Having proven to be promising and innovative, digitization 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 museum 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, give heritage institutions in Europe the chance to achieve greater visibility for their collections and engage with a wider audience. Digitization offers a range of benefits to Europe's cultural heritage institutions 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 and life-long training, tourism or gaming to attract new audiences and generate additional revenue streams:

Accessibility

To allow for global digital access to collections and research results. Numerous objects, of which only a fraction is displayed in museums, can be scanned, classified, and documented in online catalogues making them accessible to education and the public at large. Especially 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 correctly be reassembled with the aid of 3D models or archaeologic objects scanned in situ and analyzed immediately.

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 can in many cases 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.

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 can be made available for scientists and interested parties due to photo-realistic 3D models. With the aid of such digital '3D conservation', objects remain accessible for subsequent generations.

New exhibition formats

Digitization (2D and 3D) enables new ways of exhibition planning and implementation through virtual museum experiences. 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

New Applications and Services

3D replicas e.g. can be used for the 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.

3D print

3D replicas can be used in printed form 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. *CULTARM3D-P*

In this chapter we describe the first step of an automated end-to-end pipeline from 3D capturing to display and 3D-print. We call it the CultArm3D-P, a fully automated color-calibrated 3D-scanner able to scan arbitrary objects at reproducible high resolution at the push of a button.

The motivation for this scanning station is to relieve the human operator from tedious tasks, such as repositioning a camera around the object and keeping track of the scanning progress to eventually ensure a complete surface coverage and stable quality. Those are challenging tasks even for expert scanning operators, especially for high resolution scanning where the scanner measurement volume (defined by the camera optics) is normally a lot smaller than the object itself, and thus the resulting high-resolution 3D model is comprised of many single scans or images. The impact of this scanning station is twofold. Firstly, the overall scanning time is effectively reduced by a high data acquisition rate with automated and parallel processing. Secondly, the automated and adaptive data acquisition enables economical use of focused camera optics, such as macro lenses. This allows the scanning task even for larger objects, and thus effectively increases resulting surface resolution and 3D model quality.

In the following subsections, first a component overview of the scanning station is given, followed by an explanation of its virtual representation that serves as a planning environment. Then, after a description of the camera image acquisition and the reconstruction of 3D models, the focus is on the technique of view planning that involves all prior steps in a feedback loop to enable the scanning station to operate autonomously.

3.1 Design and Component Overview

The components of the CultArm3D scanning station can be classified into capturing and positioning devices, which are synchronized and controlled by a standard PC. For capturing, a high-resolution photo camera is combined with a customized mounted ring light and an optional background light. The camera must feature a PC control interface for triggering and transferring the images, such as the Canon 5DS R (50MP) or the PhaseOne iXG (100MP). For positioning, a light-weight robot arm holding the camera is combined with a turntable for the object. Thus, the object can be captured from all sides while movements of the camera can be restricted to one side of the turntable and the robot arm is not required to reach over the object for capturing it from the other side, resulting in a safer workspace and enabling the use of a static photo background. The positioning devices must also feature a near real-time PC interface, such as the collaborative robot arm series from Universal Robots.

Fig 3.1.1: CultArm3D-P as desktop version

There are currently two versions of CultArm3D scanning station available, one light-weight compact desktop version (see figure 3.1.1) and one heavier out-of-box version that comes with a centerless glass turntable. While the first version features a space-saving flat turntable, second version enables capturing the object even from below through a glass plate in one scanning pass without having to reposition it. This further reduces manual interaction with, e.g. fragile objects that cannot simply be repositioned upside-down or sideways.

Fig 3.1.2: CultArm3D-P front and back light

The custom designed ring-light has a D50 spectrum suited for color calibration with attachable polarization filters for capturing shiny or other challenging objects without specularities. The ring-light is used at close distance to illuminate and dissolve even cavities while the automated surface-adaptive robot motion guarantees a steady distance to the area in focus and thus a uniform light intensity throughout the whole scanning task. An active backlight can be optionally installed to support object segmentation from the background. Figure 3.1.2 shows both lights in operation, the ring-light at close focus distance and the back light for capturing the object's silhouettes from far distance.

3.2 *Virtual Representation and Planning Environment*

All relevant hardware components are spatially modelled and integrated into one virtual 3D monitoring and planning environment (see figure 3.2.1). The viewer shows the actual robot pose and the resulting camera angle by processing essential robot sensor readouts in near real-time and combining them to a human conceivable virtual 3D representation of the present reality. Furthermore, future scanning actions are planned and visualized (as a green transparent overlay). Intermediate scanning results are displayed within the cylindrical object safety volume (orange transparent overlay) and updated as soon as they are reconstructed and become available to provide a visual preview and indication of the scanning progress.

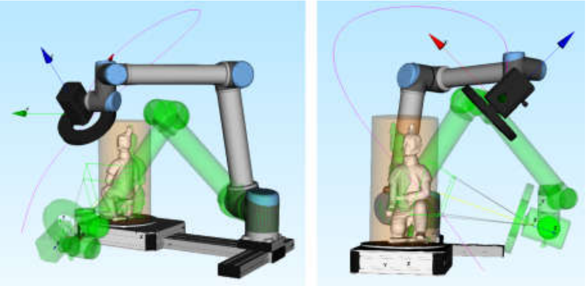

Fig 3.2.1: CultArm3D planning environment

In particular, techniques of analytical forward and inverse kinematics are applied to plan transitions between consecutive camera views and the implied robot trajectories in a safe and time-efficient way. For this reason, all vital robot parts are also augmented with colliders, i.e. surrounding geometric primitive, for rapid prediction and avoidance of collisions (see figure 3.2.2). In this way, camera views that would compromise the object's safety are either automatically rejected or rearranged [3].

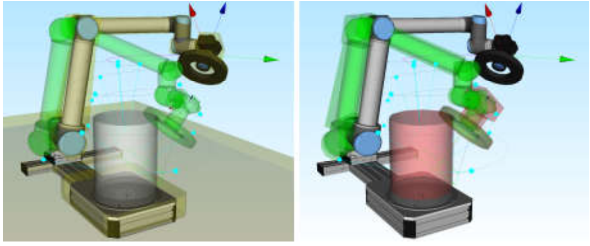

Fig 3.2.2: Trajectory planning with collision detection and avoidance (left: surrounding colliders in yellow, right: detected collision in red)

3.3 *Initial System Calibration*

To further increase the precision of the planning and scanning results, the previously defined and modelled spatial transformations from the virtual 3D representation between different parts (such as turntable, robot, and camera) are refined and corrected by an additional geometric calibration phase.

This scanning station is mobile deployable and quickly installed at new scanning locations with different camera lens combinations. However, this usually requires to temporarily unmount the camera using the quick release adapter, or to detach the robot arm from the turntable for compact packing, and this will result in a slight change in the spatial transformations and camera intrinsics when reassembling parts of the station. Therefore, the CultArm3D scanning station can compensate for this change by an initial system self-calibration that automatically carries out the following three steps in order:

1. Camera intrinsics calibration
2. Hand-eye calibration
3. Turntable calibration

First the camera intrinsics are retrieved based on [4] defining the actual field of view and compensating the lens distortion. Next the hand-eye transformation between the camera's optical center (eye) and the robot's tool frame (hand), where the camera is mounted at, is retrieved based on [5]. Using the robot arm limp calibration, which is usually provided by the manufacturer, the optical center of the camera can now be positioned with respect to the robot arm base. In order to position the camera with respect to the object on the turntable, a final step, the turntable calibration is carried out to find the surface and the rotation axis of the scanning volume. All essential calibration data is automatically acquired after placing a calibrated ring-board target on the turntable.

After the geometric calibration is complete, the camera is characterized for color by replacing the calibration target with a known color board (such as X-Rite ColorChecker SG for normal setup or Rez Checker Target for macro setup) and capturing it within the scanning volume at the desired fixed focus distance with the ring-light illumination.

3.4 Image Acquisition and 3D Reconstruction

The CultArm3D scanning station reconstructs 3D models using the established technique of photogrammetry. Therefore, the acquired raw data consists of high-resolution photos of the object, covering each surface part several times, in order to use structure-from-motion [6][7] and multi-view-stereo [8][9] techniques to recognize features and triangulate 3D information. In general, for a set of photos with complete surface coverage, the higher the camera image resolution, the higher the resolution of the resulting reconstructed 3D model. Hence, for highest resolution focused camera macro optics can be applied even for objects much larger than the actual camera measurement volume (defined by field of view and depth of the field) and capturing only a small part of the object surface per image but in high resolution. The drawback of this method is that, because of the small measurement, much more photos are necessary to cover the complete surface. This trade-off between time and quality is addressed by this scanning station.

At the current state the CultArm3D scanning system captures a high-resolution image in average every 4 seconds (approx. 900 images per hour). The images are directly transferred via USB3 connection and stored in a project folder for further processing. For small camera movements between views, e.g. during focus stacking, the system's acquisition speed becomes mostly limited by transfer speed of the camera. To achieve this high acquisition rate a state machine is modelled in software that synchronizes different hardware and software components, such as camera, lights, robot arm and turntable, reconstruction, view, and trajectory planning modules. Images are captured and processed in groups, allowing for parallelization, e.g. capturing the next group while processing the previous group.

In comparison to other 3D reconstruction techniques, such as structured-light or spacetime analysis for laser triangulation, photogrammetry is computationally expensive, normally resulting in long processing times of several hours for the final full resolution model. Therefore, the final 3D model in highest quality based on the full resolution images is usually calculated offline after the data acquisition process with the automated scanning station finished. In order to predict an adequate reconstruction quality for the final model and ensure complete surface coverage, intermediate low-quality 3D models are reconstructed in clusters already during the scanning task and they serve as a quality indicator and a decision base for further scanning actions.

3.5 View Planning

Especially in the cultural heritage domain, objects are very unique and vary in size and shape. Therefore, the scanning strategy and the camera views cannot be simply predefined but have to be carefully adapted to the individual object to achieve best results.

In this scope, view planning describes the process of computing a sufficient set to camera views in position and orientation that captures the object of interest as completely as possible, resulting in a 3D model with the desired quality [10]. This can even be an incremental process involving a feedback loop of planning, capturing, and reconstructing, where the intermediate incremental reconstruction serves as the input for the next planning phase. It can also be regarded as an optimization problem, with the objective function of maximizing an overall model quality estimate while satisfying the safety constraints. The challenge however lies in the definition of a proper quality estimate that can be frequently evaluated during the scanning process and predicts / correlates with the desired quality of the final 3d model.

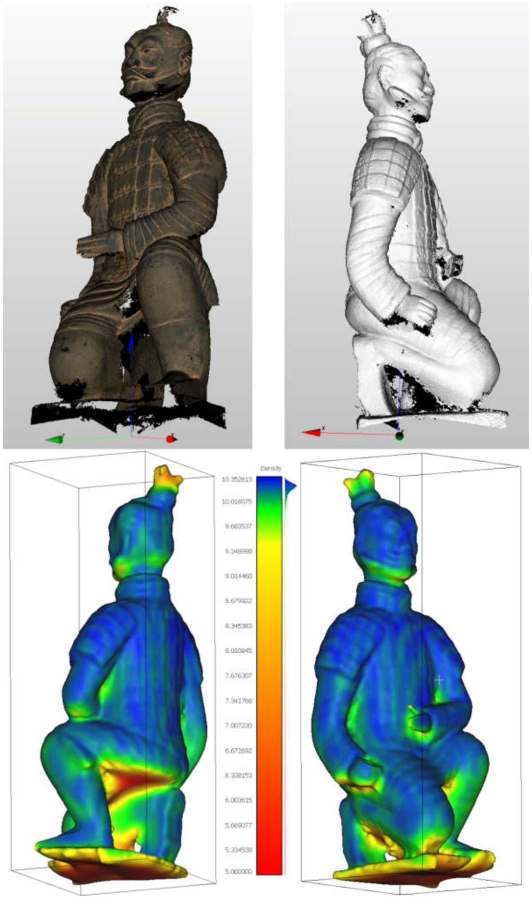

Fig 3.5.1: Intermediate 3D reconstruction results with surface density estimation

The CultArm3D features a hybrid approach that relies on little initial user input of setting a bounding and safety volume by defining a cylinder in height and diameter around the object on the turntable. Then a first set of approximated views can be quickly calculated and carried out mainly based on the volume size, the camera field of view and focus distance. Figure 3.5.1 shows the intermediate reconstruction result from an initial quick scan with 40 images reduced to low resolution. The point cloud density is automatically evaluated and low-density areas and holes are identified (and highlighted with red color) and can be distinguished from areas with sufficient density (blue color).

Based on the intermediate 3D reconstruction, a second more detailed set of views is planned utilizing rendering technologies and the calibrated camera intrinsics to simulate the effect of each view candidate. Figure 3.5.1 shows how the camera depth of field is visualized on the object. The view candidates are selected in such a way that the area in focus, which correlates with the local density gain, is maximized. Special attention is given to the previously identified low density areas that are often caused by occlusions. Additional views candidates are generated targeting those areas to eventually reach a sufficient density. With this new set of selected view candidates, the next scan phase can be carried out by the robot and the intermediate 3D reconstruction is updated. The process repeats until the desired surface density.

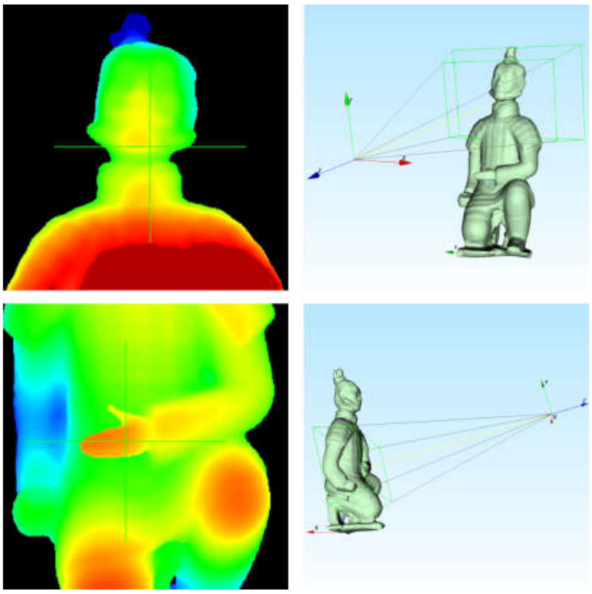

Fig 3.5.2: Depth of field estimation of two camera view candidate (green: optimally focused, blue: far plane, red: near plane)

A strong correlation was found between the density estimate on an intermediate point cloud and the surface quality of a resulting final 3D reconstructed with images in full resolution. Furthermore, careful focus planning is essential to the quality gain of intermediate and final 3D model, especially because the use of lens autofocus focusing functionality is not recommended for photogrammetry because it changes camera intrinsics for each view resulting in incomparable camera images. Therefore, the lens focus stays fixed throughout the whole scanning task while the robot automatically adapts the distance to the surface with respect to the selected camera view candidate.

4. *RESULTS*

In this chapter we present the results of some challenging digitization projects and our workflows.

4.1 “Roseninsel” – Starnberg Lake, Bavaria

The Rose Island is a small island in the Starnberg lake in the state of Bavaria, where the royal villa, the “Casino”, was built in 1853 on request of the king of Bavaria, Maximilian II. He was a passionate collector of antique findings, which he was showcasing in the dining room of the Casino [11].

While the association “Der Foerderkreis Roseninsel Starnberger See e.V.” aims to restore the “Roseninsel” island to its original state, the Bavarian Palace Department does not support this objective due to numerous reasons - fire protection, possible damage caused by visitors, and thus insurance-related questions that stand in the way. Therefore, they took the decision to commission Fraunhofer IGD to create 3D replicas of five original exhibits in cooperation with the Archaeological State Collection and display them instead.

Fig 4.1.1: Roseninsel original objects.

The CultArm3D-P table-top version is designed to acquire 3D data of cultural heritage objects up to a size of 40cm. Images were captured with a Canon camera system (Canon 5DS R, EF 100mm Macro USM), which was mounted on a lightweight robot arm. Lighting environment was realized with two large softboxes to ensure soft homogenous illumination of the objects. Objects were placed on a turntable, which was synchronized with the capturing system. The system captured around 400 images, which were later used in image-based 3D reconstruction.

Fig 4.1.2: Original Oil Lamp / Virtual color-calibrated Oil Lamp.

The complete workflow for photogrammetric 3D reconstruction consists of three main steps:

1 Calibration: Intrinsic camera calibration and color calibration through ICC profiles (characterization of the image sensor for a specific lighting environment).

2 Image acquisition: The autonomous scanning system calculates camera positions using next-best-view planning for the individual shape and size of the object automatically.

3 Processing: Captured RAW images are converted to sRGB color space based on the ICC profile generated during calibration. Image masks are automatically generated based on the image background and sharpness of the image and applied to remove the image background content. The data from all previous steps is used in the image-based 3D reconstruction workflow, which involves Structure-from-Motion, Multi-View Stereo, Surface Reconstruction, and Texture mapping.

Fig 4.1.3: 3D-replicas using Cuttlefish 3D printer driver.

The 3D printing workflow loads a textured 3D model and computes the material arrangements encoded as 2D image slices to control a multi-material photopolymer 3D printer. We used a streaming-based pipeline in which sRGB-textures were loaded, the model was voxelized, sRGB colors were transformed into CMYK tonals using an ICC color profile for each voxel, 3D halftoning of CMYK tonals was applied to each voxel and finally 2D image slices of print material arrangements were sent to the 3D printer's firmware to be printed.

The pipeline was encoded in Cuttlefish (Version 2016) [12] and used by the 3D printing service Alphacam [13] that printed the models.

4.2 JAVA Gold – rem Mannheim

Gold is extremely difficult to digitize due to its highly reflective material properties. In a project with the Reiss-Engelhorn Museums in Mannheim, Germany, we used our CultLab3D-P scanner to capture 20 very small gold artifacts from the island of Java in Indonesia, ranging from rings, earrings to bracelets in extremely high resolution with faithful color reproduction, so they would be displayed on 65" autostereoscopic displays in the exhibition showing their creators' craftsmanship and enormous attention to detail.

Fig 4.2.1: Java Gold Exhibition: Earring with mythological Daemon, Java 14.-15. AD. © CES / 3D-model: Fraunhofer IGD.

The reason why highly reflective surfaces are so hard to digitize, a problem equally found in structured light systems and the image-based approach of photogrammetry used by CultArm3D-P, is that both systems draw their knowledge of geometric depth from triangulation that is based on active or passive coding of the target surface. In the first case, structured light is overlaid over the surface to allow spatial decoding, and thus a correlation of points on the encoded surface and the corresponding pixels in the camera image. In the second case, fine structural patterns already existing on the object surface found in one image are identified on the same exact surface location, observed from several different camera perspectives, again serving as a basis for correlation of surface points and camera pixels for triangulation. In the case of reflective surfaces, the signal cast on the object surface, be it structured light or simply diffuse light required for photogrammetry, is reflected back to the camera, leading to overexposure of the sensor. Reducing exposure time, closing the aperture or reducing the light source intensity still leaves bright sensory readout in the regions of high reflectivity, depending on the camera and light angle in relation to the surface normal, while other regions are underexposed, leading to no usable correlation information. Instead of trying to find a suboptimal tradeoff between the components involved, we simply separate the received light feedback into the desired (diffuse) component, and the undesired (specular) channel. We can then use the purely diffuse information to extract geometric information, while entirely shutting out the specular compound. We achieve this by exploiting the physical effect of circular polarization, which is also used in photography. The effect only exists for mostly parallel light and observer direction (camera), which additionally implies that the light source must be as close as possible to the camera. We satisfy this requirement using diffuse ring lights of our own design which surround the lens, providing a narrow band of diffuse light around the lens aperture. Both the light source and the camera lens are equipped with circular polarizers that are tuned so that they let the diffuse light component pass while blocking the specular component. The effect is based on the fact that light originating from the light source and being directly reflected off the target surface is phase-shifted during the reflection, and cannot pass the polarizer in front of the camera (analyzer) which is tuned accordingly. All other light contributions that are reflected by the surface but find their way under different angles and numbers of reflections, pass the analyzer, and contribute to a well-lit diffuse image.

Fig 4.2.2: Java Gold Exhibition at Reiss-Engelhorn-Museen; © CES / 3D-model: Fraunhofer IGD / United Screens GmbH.

5. CONCLUSION

We presented our CultArm3D-P, an autonomous, color-calibrated 3D scanning robot yielding reproducible high-quality 3D models as an example of how to put automated 3D mass digitization for the digital preservation of entire collections to practice. In line with the overall objective of the European Commission’s Digital Agenda for Europe, our approach provides a solid foundation for future research and development of 3D technologies in the realm of cultural heritage. The system is highly flexible and can come in multiple configurations using glass turntables to scan from below or turntables on the floor to increase the scanning volume and allow for heavier artifacts. It serves as a platform for future improvements and the inclusion of advanced technologies (e.g. volumetric measurement sensors, ultrasound or others) towards 3D consolidated data models and therefore represents an important contribution to leveraging innovative digital technologies for the cultural heritage sector. The conducted work marks an important milestone in the journey of cultural heritage research towards a connected and digital future. It fosters new applications using high-quality 3D models which range from better visitor experiences in museums by innovative exhibition concepts based around 3D replicas, to new business models such as ‘virtual loans’ of 3D models or educational applications. Our CultLab3D developments offer the chance for cultural institutions to tap into additional revenue streams and secure their funding with complementary business models and enable digital heritage preservation and research for future generations to come.

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