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Digitising Ivory Artefacts at the National History Museum in Brazil

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Figure 1: *Two renders of the final 3D model of the boat, one with the windows (left) and one showing the interior (right).*

Abstract

The advantages of digitisation technologies, such as 3D scanning, photogrammetry and 3D modelling, for the documentation and dissemination of cultural heritage artefacts is well understood by researchers. Nevertheless, practitioners, in particular those in developing countries, still have a lack of understanding of how 3D technologies could work for them in order to support their collections. This paper presents ongoing efforts to engage with museums in Brazil, in particular the National History Museum in Rio de Janeiro, in order to raise awareness of the potential of 3D technologies. Rather than applying 3D digitisation technologies on artefacts where it is known that the techniques can provide an easy solution, our approach was more experiments. Hence, several ivory artefacts were selected, including various figurines and a carved Junk Boat from East Asia which are part of the museum collection and which present particular problems both in terms of conservation and dissemination. The artefacts are complex and difficult to access. Nevertheless, the intention was to provide practitioners at the museum a good understanding on the advantages and limitations of the technologies. The contribution of this paper is the exploration of the use of 3D digitisation technologies for the documentation and dissemination of ivory carvings from a Brazilian perspective. The paper includes a discussion on the challenges in terms of having access to suitable infrastructures to support documenting, monitoring and dissemination of heritage artefacts at a larger scale within the Brazilian context.

CCS Concepts
•***Computing methodologies*** → *Computer graphics;* •***Applied computing*** → *Arts and humanities;*

1. Introduction

Heritage organisations across Brazil care for a wealth of tangible heritage material from the country's rich past. Followed by more than three centuries of Portuguese rule, the Brazilian declaration of independence in 1825 enabled the new country to establish diplomatic ties with other European powers. Since then, immigration has been seen as the means to improve a nation that has been tainted by the history of Portuguese colonialism and African slavery [Les13].

As a result of Brazil's multi-cultural history, a rich variety of heritage artefacts are cared by Brazilian public organisations. The preservation and dissemination of these artefacts to wider audiences often face multiple challenges. Firstly, funding is low and there is a general lack of knowledge on how to take advantage

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of digitisation technologies to support museum professional practices. Secondly, the environmental conditions of cities, such as Rio de Janeiro, present particular problems for the conservation and preservation of artefacts. In particular, environmental issues such as temperature and humidity create challenging conditions when storing or displaying artefacts. The problem might exacerbate when artefacts need to travel or be on temporary loans.

Despite the challenges, Brazilian tangible heritage represents the multiples histories, cultures and traditions of Brazil's citizens. Promoted to a national and global audience, these assets can become a useful resource with which to support the educational, socio-cultural and economic development of the country.

This paper describes ongoing efforts to engage with museums in Brazil, in particular the National History Museum in Rio de Janeiro, in order to raise awareness of the potential of 3D technologies by providing them with selected and suitable artefacts. The National History Museum, created in 1922, is one of the most important museums in Brazil, consisting of over 348,515 items. Revitalized in 1987, the permanent circuit of exhibitions is divided into two thematic modules, dealing with the economic and social aspects of the history of Brazil.

The aim of the project was to build capacity within the museum to support the uses of 3D technologies for the documentation, research and dissemination of heritage artefacts. Of relevance, the project aimed to understand the requirements for infrastructures which enable museums in Brazil to deploy 3D technologies at a larger scale. The museum was particularly interested in exploring the application of 3D technologies for a collection of ivory made artefacts. The collection (see Figure 2) contains eighteenth-century East-Asian carvings. Some of these artefacts were given to the infant Prince Pedro who became Brazilian Emperor Pedro I in1822. Other artefacts have Indo-Portuguese Catholic religious imagery, which are important documents on Western and Eastern relations in the context of the Portuguese Overseas Empire.

Figure 2: *Ivory artefacts from the National History Museum collection*

The paper's main contribution is the exploration of the use of 3D digitisation technologies for the documentation and dissemination of ivory carvings from a Brazilian perspective. The paper is organised as follows. Section 2 explains the background of the collection as well as the tradition of ivory carving. Section 3 explains related work on digitising complex and intricate artefacts. Thereafter, Section 4 describes the technical developments and results of the digitisation efforts conducted in collaboration between academics and practitioners at the National History Museum. Section 6 discusses user feedback as well as the challenges for future efforts to incorporate 3D digitisation technologies into museums' and heritage organisations' practices within the Brazilian context. Finally, Section 7 presents conclusions and further work.

2. Background

Carving is the process of shaping a piece of material by using a tool to remove portions of the material. The technique can work using any material which is solid enough to hold a form even when pieces have been removed from it and yet soft enough for portions of material to be removed from it. Until digital technologies were introduced (e.g. CNC machining) carving was completely a manual processes which involved using tools such as chisels and knives.

The art of ivory carving, although damaged nowadays by the illegal trade of ivory tusks, is a long human tradition which has survived since pre-historic times. In China, this art developed to its finest form. Europeans stimulated the Chinese ivory industry from the 16th century on, and often taught carvers how to sculpt Catholic motifs such as the Madonna, Christ on the cross and various saints [MS03].

In the 18th century, Chinese artisans - under the patronage of the emperor and dictated by his royal taste - created a very unique courtly style for ivory carving. The designs were a mix of elaboration and restraint by using intricate motifs. Knife work, grinding and polishing were used to create a variety of artefacts including combs, jewellery, paper-knives, chess sets and Chinese junks or boats. These artefacts often included dynamic mechanisms. For instance, chess pieces were carved as puzzle balls which contained a series of concentric layers of freely rotating carved balls, one within another.

Chinese junks were a popular artefacts for carving. A junk is an ancient Chinese sailing ship. Carved junks will often have masts, flags and human figurines at doors and windows as well as on the top deck. The junks also incorporate intricate windows designs which enable the viewer to see inside.

The museum is currently organizing a new exhibition for the ivory collection that will emphasize the historical relations between Brazil and the Orient. Hence, the museum's collection of ivory artefacts was used during a first dialogue phase where the project's goal was decided. During this time, computer graphics experts, museum curators and researchers came together to discuss the different options for 3D digitisation and to increase the overall technology awareness of the team. A selection of two ivory carved artefacts, including a figurine and a Chinese junk, were selected to be digitised. The carved Chinese junk curated by the National History Museum is shown in Figure 3, and measures approximately 1 meter lengthwise.

The selection of the artefacts for 3D digitisation was driven by the need to explore the potential of 3D digitisation technologies in order to support:

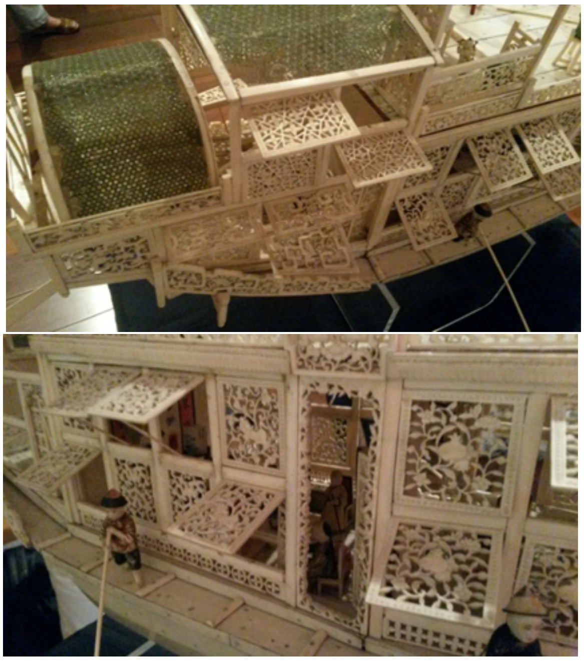

Figure 3: *Chinese Junk at the National History Museum.*

1. the documentation of the artefacts,
2. the conservation of the artefacts, as some of them appear to be affected by humidity and small cracks have started appearing on them.
3. the public dissemination, as it is very difficult for audiences to have access to the Chinese junk in order to appreciate the full artefact, including its interior and exterior.

The following section will describe previous work on the digitisation of ivory artefacts and other complex surfaces such as those presented by the Chinese junk boat.

3. Relevant Work

Bright specular surfaces, such as ivory, are usually troublesome when using conventional 3D digitisation techniques to capture their surface. 3D scanning techniques, such as white light scanners and laser scanners suffer with light refraction when it bounces of shiny surfaces. Relevant algorithms attempt to estimate and remove error, but to date scanning is still problematic under these circumstances.

A second challenge presented by the artefacts is its intricate carving and lattices. Using scanning or photogrammetry is a complex task because of various factors, including:

- carved structures can create many severe self-occlusions;
- fine details might not be properly recovered by the scanners due to their intrinsic resolution limitation;
- the repetitive nature of the carved patterns might pose challenges for the alignment of photographs in a photogrammetric process;

Objects which are similar to ivory carvings are normally referred to as intricate objects or filigrees [CZX*16] in the computer graphics literature. Previous work to digitise intricate objects have focused mainly on the use of cast shadows as informative cues to the shape of objects [LCH13, YNBK07]. Moreover, Chen et al. [CHOC08] demonstrated that 3D carvings can be achieved by extrapolating lines and curves from line drawings using edge detection and scan line algorithms on images. CT scanning technology has also been proposed as a technique for exploring the interior of ivory carved artefacts [LBM*13]. Another approach is proposed by Pasko et al. [PSS01] which demonstrated that procedural and functional models can be used for synthesising relief carvings based on relief depth data.

4. 3D Digitisation of Ivory Artefacts

The approach that was used for the 3D digitisation of the collection uses a combination of approaches. Digitising the figurines used a simpler process than the one required for the Chinese junk. For the latter, it was not possible to deploy previous solution based on shadow as the digitisation took place at the museum with severe limitations on the ability to move the object as well as challenging climate conditions for the digitisation equipment. Hence, the team decided to collect digital photographs in order to experiment with photogrammetry and synthesising approaches informed by the images. The following section will explain these developments as well as how suitable they were for the problem presented by the museum.

4.1. 3D Scanning of Artefacts

Figure 4 illustrates one of the objects that was digitised using a Minolta Vivid 9i scanner, and texturised using a set of 15 photos. All post-processing to reconstruct the surface and texturise the model was done in Meshlab. In this case, the statue had already partially lost its brightness and the scanner was able to cope well with the light surface. Nevertheless, small fissures and cracks were lost due to the limited resolution of the laser, but could be partially seen after the texturisation.

For the Chinese junk, however, the possibility of using laser scanners was soon discarded, since the available device is not able to capture the fine details of the structure and the panels.

4.2. 3D Modelling of Chinese Junk

Synthesising the Chinese junk geometry based on the digital photographs was deemed the only suitable solution given the constraints presented. Hence, the Chinese junk was modelled using the opensource Blender software. Firstly, the main structure was created using traditional modelling techniques, such as, extrusion, subdivision and vertex, face and edge manipulation. Photos were used as reference. More specifically, a profile and a frontal digital photograph were used concomitantly as scale references for the main structure. In the same manner, other small decorative objects were modelled. Figure 5 shows a rendered image of the junk's main structure and some of the smaller figurines. The materials for the models were inferred by visual inspection of the physical object, as well as from the photos. Final renders of the Chinese junk structure are shown in Figure 1.

Figure 4: *From left to right: three ivory pieces that contain clear signs of degradation, and a 3D model of the last object.*

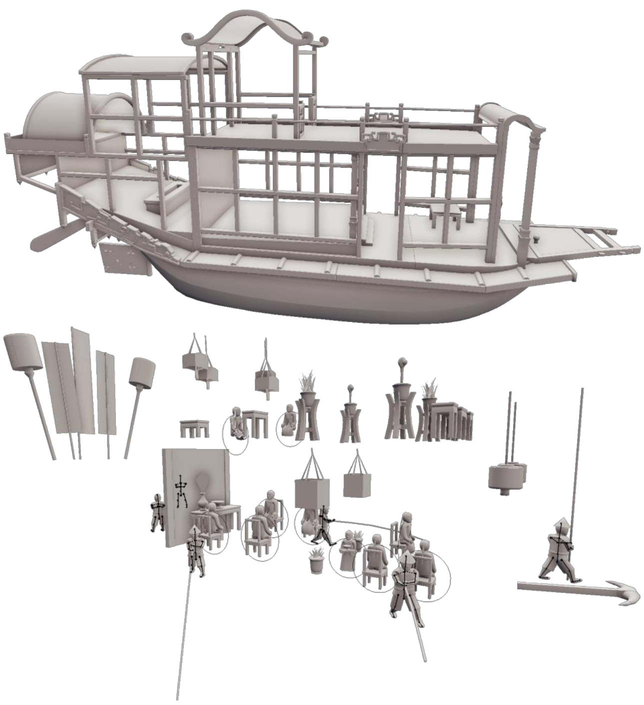

Figure 5: *The main structure of the Chinese junk's 3D model, and some of the decorative elements.*

4.3. Digitising the Intricate Window Panels

The delicate structure of the Chinese junk did not allow for any sort of manipulation of its pieces, such as opening or closing the windows, or even placing some constant background behind the windows to facilitate its reconstruction. The available 3D scanner technology had inadequate resolution to capture the windows details, and photogrammetry methods resulted in very noisy models (see Figure-8.) Even worst, the noise had the same magnitude as the windows high frequency details, thus rendering its removal impractical.

Figure 6: *A resulting 3D model of a window panel using photogrammetry techniques. At a first glance the acquired point cloud would attend the demands, but underlying noise always entailed in low quality geometric reconstructions.*

Clearly, digitising the intricate window panels required a different approach than the one used for the rest of the body structure. When observing the junk boat in more detail (see figure 3), it is clearly evident the complex yet repetitive nature of the window panels. With regards to the quality of the digitisation output, the museum had the requirement to explore the use of 3D techniques for the dissemination of the boat by using a variety of approaches, such as rendered videos and 3D printing. Hence, it was deemed important to acquire geometry and the visual information of the window panels' surface in a way suitable for rendering or 3D printing.

Although the windows seem to be repeated in many instances, each carving has its minute imperfections as a result of a manual process. Therefore, it was important to incorporate the images into the modelling process in order to accurately depict the carved geometry. This approach was deemed more suitable than manually modelling the complex and intricate carving of each window.

A custom method was designed to create a 3D representation of the windows by incorporating the digital photographs into the process. It was assumed that orthophotos, or the image geometrically corrected such that the scale is uniform, can be used to generate an elevation or heightmap. In addition, it was assumed that the windows have a uniform colour and that the light is being projected orthogonal to its surface. Thus, the lighter regions of the windows are closer to the camera and the darker regions are further away.

Firstly, a frontal image of each window was processed to prepare it for the reconstruction process. For this, the image was cropped, perspective correction was applied, and the foreground was segmented from the background using Gimp.

Based on the work by Lengyel et al. [LPFH01], a 3D representation of the carved windows was produced with a good visual quality by creating a shell structure which is generated using array of planes. This was achieved by the following sequence of steps:

- generate a binary map with the background information so that the texture can contain an alpha channel in order to display the transparent areas correctly;
- generate a normal map with the colour image;
- create a geometric quad;
- map both texture map and material properties to the geometric quad; and
- configure the windows thickness by stacking multiple copies.

The multiple slices of quads were stacked to give the impression of a volume while maintaining the correct transparency at every level. Ten slices were used for each window panel. A rendering of one of the boat's window using this method is shown in Figure 7.

The approach described above was suitable for the requirements of visually good rendering. However, it did not generate 3D geometry in a way which was suitable for 3D printing. In order to explore the suitability of 3D printing for presenting alternatives representations of the Chinese junk boat, the team experimented in reproducing some of the windows.

To address the needs for producing 3D geometry, the binary map previously described was used. Instead of depicting the background information, a semi-automatic process for vectorising the foreground information was used (see Figure 11). Thereafter, Blender was used to extrude the vectorised data in order to provide thickness to the vectorised image. This 3D mesh (see Figure 9) was suitable for 3D printing. However, the mesh lacked the carved details on the surface of the window.

To address the challenge of generating geometry for the surface carving, the image depth map was used. The depth map was useful as it contains information relating to the distance of the window

Figure 7: *One of the Chinese junk's window rendered using the proposed method.*

Figure 8: *Vectorized window image to generate 3D geometry.*

panels from the camera viewpoint which were estimated by looking at the brightness variance over the surface.

An orthogonal image which uses a combination of pixels from front facing images (as shown in Figure 10) was generated in order to create a depth map. The images that were selected were all taken from slightly different camera angles. Hence, they were aligned using a SURF feature description extraction method which enables to compute a perspective transformation to align different images into one single image. The background was then removed and a depth map calculated in order to produce a 3D mesh of the surface using a mesh extraction tool.

Finally, the resulting mesh was 3D printed, as shown in Figure 8, using a Makerbot Replicator 2X. The resulting 3D mesh contains the surface details with a good visual quality. However, the distortion on the images was not completely eliminated. It was considered that a method which combines both vectorised image

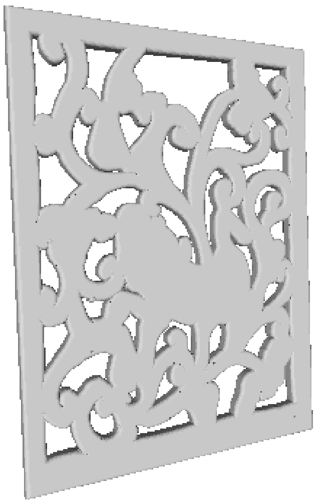

Figure 9: *Vectorized image and resulting 3D mesh.*

Figure 10: *Multiple images used to create a depth map for creating a 3D model.*

and depth map information would need to be further investigated to combine both sets of data.

Figure 11: *3D printing of 3D mesh produced by using a depthmap of the digital photographs.*

5. Website

As a result of the collaboration with the National History Museum, a website was set up to hold its products. It contains videos of interviews with the museum practitioners and the 3D visualisations of the digitised artefacts. Figure 12 shows the entry page of the website.

The videos present the historical background regarding the trade relations between Brazil and the Orient, and the oriental influences in Brazil. One of the videos talks in particularly about the ivory trade and art, and the museum ivory collection.

The user interface allows the user to inspect the 3D model of the Chinese Junk (see Figure 13). The interactive interface was produced using the Unity game engine. It is possible to rotate the Chinese junk's 3D model, remove the panels to see the interior, and click on hotspots to acquire more information. The hotspots give more details on the window panels and their relation with the Chinese culture, such as the figure of the bull, pomegranate, swastika, bat, dragon, phoenix, lanterns and ancestral cults. Figure 14 illustrates the activation of three hotspots.

Figure 12: *The front page of the Website with the results of the project, where it is possible to click on the Chinese junk image to go to the 3D interactive page, or watch one of the four related videos. From left to right the four videos are: The Orient in Brazil, Oriental Types and Fashion, Trade in the Indian Ocean, Ivory: History, Art, and Violence.*

The resulting 3D model and website of the Chinese junk will play a central role in the forthcoming museum exhibition. Thus, a kiosk with the interactive 3D system and the videos will be included as part of the exhibition. For guided tours, especially for school visits, the 3D prints will be used as complementary material to be passed around the visitors, enriching the experience.

6. Discussion

The project's main outcomes were twofold: increased awareness of the benefits of 3D technologies within the context of heritage preservation; and a complete product case that can enrich the dissemination practices and a specific exhibition of the museum. Using the ivory collection to explore these issues was a risky decision as the team knew that there will be limitations on what the technology could achieve. Nevertheless, it was considered that it was important to demonstrate to the museum staff the capabilities of the different technologies to produce 3D data.

Figure 13: *The 3D interactive section of the Website. Top image shows the 3D interface, where it is possible to rotate the virtual model in four directions, activate the hotspots ("verbetes"), and toggle the panels to see the interior ("VisÃčo Externa"). Bottom figure shows the Chinese junk without the panels.*

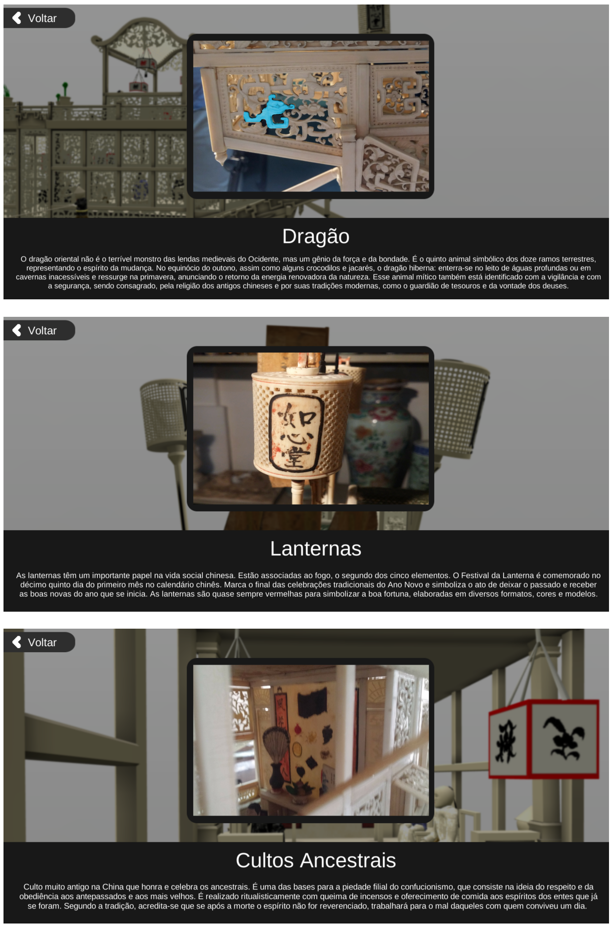

Figure 14: *When clicking on a hotspot, the 3D model is automatically rotated to the corresponding position and a detailed photograph and textual information is shown. The three depicted hotspots are: the dragon, lanterns, and ancestral cults.*

That the laser scanner would fail to capture the fine details of the panels, for example, was truly comprehensible. Better devices could eventually lead to capturing the finer details, but we expect that in the context of Brazilian museums more affordable solutions are necessary. We were, however, set back with the photogrammetry results, that were expected to have reached finer results. Many different light configurations and camera setups (e.g. using macro) were experimented, but none led to truly satisfactory results. We do expect, however, that with better cameras and a more controlled light environment the results could be improved.

Working conditions were, unfortunately, not ideal. The objects were digitised in the museum's technical reserve, but the room has no air conditioning, and the bulk of the work was carried out during the summer months in Rio. During this period ambient temperatures commonly arrive over 35 degrees Celsius, and the effect is aggravated by the heat from the light sources for photographs. Excessive heat has a significant negative effect on the artefacts, the equipment, and the digitisation crew. These conditions will not be very dissimilar to conditions on other museums in Brazil. Hence, environmental factors such as heat and humidity as well as the limitations of access suitable digitisation equipment will pose a serious problem for the wider adaptation of these technologies.

The geometric complexity of the Chinese junk presented additional challenges. Even if photogrammetry would have produce satisfactory results for digitising the panels, creating the whole 3D model in finer details with this technology was out of the question. There are too many details and places that are unreachable for the camera. Despite this, the museum staff were very satisfied with the 3D model created using the ad-hoc solution described in this paper. The total time spent in producing the 3D model was of approximately one a half month of a modeller's time, and the images for photogrammetry trials were taken in 5 different sessions, each one ranging from 4-6 hours. This was, nevertheless, only a small fraction of the time spent on the project. Other times was spent digitising other ivory artefacts as an entry showcase for the museum, discussing and meeting with the museum staff to select the main project theme, photogrammetry trials, historical research, video production and editing, and creating the website interface. In total, the project time was of nearly one year.

The potential of 3D technologies for dissemination purposes, especially when the resulting 3D visualisation is available on the web, was clearly evident to the museum staff. However, the potential for the 3D models to be used for conservation purposes needs further exploration. This is because the quality of the 3D scanned models is limited and 2D imaging technologies might provide cheaper and more accessible alternatives to solve the same problem given the limitations of the Brazilian museums.

One not immediate outcome of this project is that we strongly believe that we have opened a viable path for the insertion and acceptance of technology into the museum's future preservation and dissemination endeavours. The feedback from their side was extremely positive, and it was very noticeable how their effort and motivation increased as the project started to take shape and generate the very first results.

Furthermore, the project highlighted that there is a lack of understanding on the challenges which are particular to developing countries, such as Brazil, in order to promote the use of digitisation technologies in the heritage sector. These challenges include the lack of awareness of technologies, the lack of understanding of the nature of heritage collections as well as the lack of suitable infrastructures. These infrastructure should provide access to equipment, space and expertise in order to further support museums in building capacity for them to undertake digitisation of collections. Addressing these challenges will be critical to provide hard evidence on the need to provide funding and investment in the area of digital heritage in Brazil and other countries which present similar sociopolitical circumstances.

Hence, we hope that such initiative will broaden the yet very insufficient access to cultural heritage in the country. Furthermore, we believe that it will draw attention to the severe preservation issues of the rich national collection, and, at the same time, increase the consciousness of how technology can be of great aid in this task.

7. Conclusions

In this paper we have presented a project with one of the most important museums in Brazil, the National History Museum in Rio de Janeiro. After raising awareness amongst the museum staff, the team deployed 3D technologies with the aim to support the documentation of artefacts in the museums. The museum is in the process of designing a new exhibition emphasizing the Orient-Brazil historical relation, and highlighting the museum's ivory collection will be a great asset for the museum. The project's outcomes included an interactive 3D web based system for inspecting the Chinese junk, an important piece of the ivory collection. It is expected that these project results will enrich the public's museum experience by accessing innovative interpretative material.

Due to the challenges that such artefact presented, we have described in this paper how we handled the respective issues to produce the final 3D model, and how different solutions were employed for rendering and 3D printing purposes. We relied heavily on manual 3D modelling for this case, but it is not a viable large scale solution, especially given the lack of financial and human resources in the cultural heritage scenario in Brazil.

Further work will involve trailing improved methods to digitise intricate carved surfaces by using combination of digital images and synthesised content. Another very interesting future direction that came out from the discussion with the museum team, was the possibility of tracking the degradation state of some artefacts. More specifically, to measure how the fissures and cracks are evolving with time, and what is the impact of taking a piece out of the museum on loans. To precisely measure the fissures with low cost equipment, such as digital cameras, is an interesting challenge that can be addressed in future research.

8. Acknowledgements

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References

[CHOC08] Chen Y., Han X., Okada M., Chen Y.: Integrative 3d modelling of complex carving surface. *Computer-Aided Design 40*, 1 (2008), 123–132. Constrained Design of Curves and Surfaces. URL: http://www.sciencedirect.com/science/article/pii/S0010448507001558, doi:http://dx.doi.org/10.1016/j.cad.2007.06.013. 3

[CZX*16] Chen W., Zhang X., Xin S., Xia Y., Lefebvre S., Wang W.: Synthesis of filigrees for digital fabrication. *ACM Trans. Graph. 35*, 4 (July 2016), 1–13. URL: http://doi.acm.org/10.1145/2897824.2925911, doi:10.1145/2897824.2925911. 3

[LBM*13] Laycock S. D., Bell G. D., Mortimore D. B., Greco M. K., Corps N., Finkle I.: Combining x-ray micro-ct technology and 3d printing for the digital preservation and study of a 19th century cantonese chess piece with intricate internal structure. *J. Comput. Cult. Herit. 5*, 4 (Jan. 2013), 1–7. URL: http://doi.acm.org/10.1145/2399180.2399181, doi:10.1145/2399180.2399181. 3

[LCH13] Lin T.-H., Chang H.-T., Hu S.-J.: 3d reconstruction of intricate objects using planar cast shadows. In *ACM SIGGRAPH 2013 Posters* (New York, NY, USA, 2013), SIGGRAPH '13, ACM, pp. 1–1. URL: http://doi.acm.org/10.1145/2503385.2503471, doi:10.1145/2503385.2503471. 3

[Les13] Lesser J.: *Immigration, Ethnicity, and National Identity in Brazil, 1808 to the Present*. Cambridge University Press, 2013. 1

[LPFH01] Lengyel J., Praun E., Finkelstein A., Hoppe H.: Real-time fur over arbitrary surfaces. In *Proceedings of the 2001 Symposium on Interactive 3D Graphics* (New York, NY, USA, 2001), I3D '01, ACM, pp. 227–232. URL: http://doi.acm.org/10.1145/364338.364407, doi:10.1145/364338.364407. 5

[MS03] Martin E., Stiles D.: *The Ivory Markets of East Asia*. Save the Elephants, 2003. 2

[PSS01] Pasko A., Savchenko V., Sourin A.: Synthetic carving using implicit surface primitives. *Computer-Aided Design 33*, 5 (2001), 379–388. URL: http://www.sciencedirect.com/science/article/pii/S0010448500001299, doi:http://dx.doi.org/10.1016/S0010-4485(00)00129-9. 3

[YNBK07] Yamazaki S., Narasimhan S., Baker S., Kanade T.: Coplanar shadowgrams for acquiring visual hulls of intricate objects. In *2007 IEEE 11th International Conference on Computer Vision* (Oct 2007), pp. 1–8. doi:10.1109/ICCV.2007.4408902. 3