Digitally Restoring Artefacts Using 3D Modelling Techniques for Immersive Learning Opportunities

Sharon Pisani
School of Computer Science
University of St Andrews
St Andrews, UK
sp259@st-andrews.ac.uk

Alan Miller
School of Computer Science
University of St Andrews
St Andrews, UK
alan.miller@st-andrews.ac.uk

Mark Hall
Perth Museum and Art Gallery
Culture Perth and Kinross
Perth, UK
mahall@culturepk.org.uk

***Abstract*—Digital heritage projects are an important tool in safeguarding cultural heritage and making it available to future generations. The work presented here synthesises 3D modelling techniques with the process of digitising artefacts. New digital reconstructions can be created based on authentic data. These are then implemented in various immersive learning opportunities, such as interactive activities and engaging virtual worlds. This is applied to the restoration of two Pictish symbol stones used in an online colour configurator tool and a virtual environment.**

***Index Terms*—digitisation, 3D modelling, immersive learning, virtual reality, digital heritage**

I. Introduction

The digitising of historical artefacts is a crucial aspect of the conservation, preservation, and interpretation of culture. Advancements in technology have made it possible to create reconstructions of the past which go beyond a photograph or digital image. Increasingly, museums are digitising their collections, turning them into 3D models through object scanning, and using them as "digital surrogates" to make the artefact accessible in the digital world [1]. 3D scans can be used to interact with the artefact in new ways: rotating, zooming in, and digitally handling the artefact, something which is not common in traditional museum settings. This closeness to the digital model provides opportunities for people to get close to artefacts. However, it is often still presented in an environment that is not representative of its original context and use, or how that may have changed over time.

Digital modelling has been beneficial in developing replicas of the past. 3D modelling software and gaming engines can build objects and environments from the ground up. This has given new opportunities to interact with the past. Presenting artefacts as realistic 3D models can help the viewer understand their historical relevance as they can be visualised better. This could further be heightened by placing them in their historical setting. The importance of 3D models in increasing public engagement, accessibility, and experience has been observed in many settings [2].

This paper discusses how digital modelling techniques can be synthesised with 3D scanning to digitally restore artefacts and create authentic replicas in their original states. Artefacts which had already been photogrammetrically scanned were restored using digital modelling software and then used in various immersive experiences. Whilst the project focuses on Pictish sculptures, namely, the St Madoes Cross-Slab (Fig. 1) and the Inchyra Symbol Stone (Fig. 3), the techniques developed can be applied to other artefacts.

The next section will provide an analysis of digitising techniques and how restoration of digital models can take place. Section III will describe how historical research shaped the decisions taken during the restoration. Then, section IV will describe how the stones were restored. Immersive learning opportunities that arise from the use of the models are discussed in section V, followed by remarks on future work.

II. Background

A. 3D Scanning Techniques

3D scanning can preserve a lot of information that a photograph cannot, such as size, texture, and surface shape. Interaction with the artefact is varied: from the use of the model in virtual or augmented reality to 3D printing and handling in physical interactions. 3D scanning of artefacts enables non-intrusive research, restoration, and exploration of theories about their use and appearance. Accurate data in 3D can be captured through photogrammetry, structured light scanning, or laser scanning.

a) Photogrammetry: Computer software can extract 3D coordinates of each point on the object from multiple overlapping photographs of an object from different angles. The spatial relationship between the points is calculated, creating a sparse-point model. The images are analysed again to create a dense-point cloud of the model. This point cloud is derived from the pixels of the image and since modern camera sensors have improved considerably, the large number of points on the model can show extensive detail. Since the data is taken from a photograph, the data points in a photogrammetry model can include colour information as well. This helps to create a digital model with accurate textures [3]. With the increase in computing power, it has become possible to handle hundreds of photos of one object. Digital cameras are readily available, and free and easy-to-use software make community-based projects a possibility [4]. Photogrammetry has proven useful in creating models of larger artefacts such as rock formations and forts [5], temples and archaeological sites [6], and stone crosses [4] amongst others.

978-1-7348995-2-8/22/$31.00

b) Structured light scanning: The position of a 3D point can be calculated by measuring the deformation of a structured light pattern that is projected on the object [7]. When scanning small artefacts, structured light scanning is more favourable than photogrammetry as it can capture more details, since in photogrammetry less photos are taken to capture the surface of a small artefact, thus capturing less details [8]. This is also the case in finely detailed artefacts [9], [10]. The downside to structured light scanning is that it cannot be used on well-lit areas or in outdoor environments where ambient light overpowers the projected light.

c) Laser scanning: 3D data points for a model's point-cloud are collected from sensors using a laser scanner and include typical XYZ coordinates as well as information about the material such as texture and colour [11]. Light Detection and Range (LiDAR) and other types of laser scanners use light in the form of pulsed laser that is emitted and received back to measure distance between the scanner and an object. Similar scanners are Time of Flight (ToF) which create a depth map based on reflections of a transmitted light that are usually captured with a camera. The popularity of laser scanning has recently surged due to LiDAR scanners in Apple's iPad Pro and iPhone range, as well as ToF scanners in some consumer android products. This has facilitated crowd-sourced projects, such as the Earth Archive project which aims to scan and map the entire surface of the Earth to digitally preserve the Earth's surface for future use [12]. Terrestrial laser scanning has successfully been used to preserve monuments and buildings [13]. Accurate replicas can be made which can help rebuild damaged buildings, like the Notre Dame Cathedral [14], and to analyse their conservation state [15], [16]. Spatial 3D models are increasingly used in virtual museums and many times, some form of laser scanning is used to achieve this.

Often, projects make use of a mix of scanning technologies, depending on the object being scanned, and the intended use of the digital model. Textures obtained from photogrammetry could also be laid over more detailed point clouds obtained through LiDAR scanning [17].

B. Methods of Restoring Digital Models

Theories about an artefact can be explored on a digital model. Non-invasive restoration and reconstruction show how an artefact looked through time. 3D scanning has been used to repair physical artefacts by 3D printing missing pieces [18]. Restoring an artefact could bring to light new ideas and link the artefact to its context. Working digitally facilitates an open workflow which keeps 3D visualisation projects sustainable and accessible as encouraged by the London Charter [19].

a) Repainting: Many sculptures were once painted with no physical remnants left today. Paint restoration work has previously been applied to digital models of Pictish stones [3]. This was done through a layered painting process which enables future experiments. Even if the result of the project is inaccurate, it can continue to develop as new discoveries are identified. Their work on medieval stone crosses had a focus of restoring the narrative function of the crosses. In fact, they chose colours which are familiar to their audience, even if there was no direct evidence of their use on the stonework. Virtual reality was used to test the 3D models. Audiences were shown unpainted and painted models and in fact, painted models were better understood by audiences. This work shows that 3D models can be used to enhance physical interaction and disseminate the historical narrative to a wider audience, immersing them in this narrative. A recoloured reconstruction of the St Madoes cross-slab was previously used in an exhibition, *Picts and Pixels*, at Perth Museum and Art Gallery in 2017 [20]. A 3D video was used to show the stone slab and it contributed to positive reactions from the audience. However, the model was painted in strong colours. Certain details were lost, and the damaged top part of the stone was not reconstructed.

b) Reconstruction: Recreating missing pieces can prove challenging depending on the affected area and the information available. Commonly, a similar item or area of the object is scanned and the resulting model is added to the missing part of the model being restored. This involves fitting the reference surface around the area of the damage by adjusting their point clouds [21]. While this method provides accurate repairs, it is difficult to achieve if the content of the missing area is uncertain. The reference material must also be very similar to the object being restored. Automated mesh editors have been developed using mathematical Poisson-based gradient field manipulation to combine meshes together [22]. However, this is limited to the framework used in the experiment. Other algorithms can enable intuitive cut-and-paste operation when editing surface meshes, where a detail from a reference mesh can be pasted onto a target surface, provided that there is a continuous one-to-one mapping [23].

This paper proposes more straightforward workflows which make editing a 3D model accessible by implementing 3D modelling techniques using computer graphical software. Digital software that allows manipulation of a mesh has been utilised before, such as in reconstructing missing bones in palaeontological scans [24]. However, our approach goes further by reconstructing missing pieces of the digital mesh and then restoring the object to its original appearance. The St Madoes stone was restored using Adobe Mudbox—a digital painting and sculpting software, while the Inchyra symbol stone, which had larger areas for restoration, was completed using Blender—an open-source 3D creation suite. The usage of these programs is discussed in IV.

C. Creating Virtual Environments

Museums are striving to incorporate virtual and augmented reality as an immersive tool for visitor learning and engagement. In the early twenty-first century, most museums dealt with audio clips and tangible activities to provide interactivity. However, the popularity of smartphones and the internet has made it possible to add an immersive layer to exhibits. People are nowadays more familiar with games and modern forms of interaction. Various projects have developed applications which are spread over the continuum between reality and virtuality. Phygital heritage describes how integrating digital technology into physical reality can enrich communication of heritage values [25]. "Parallel reality" describes how a user can be present in the virtual and real worlds simultaneously [26]. Walking around a physical environment enables the exploration of its digitally restored reconstruction. Here, users do not need to switch between the real and virtual worlds in order to navigate them, but they do need to physically be at the location [27].

Other applications in museums and online are fully virtual and can allow users to experience heritage anywhere. The preferred style in such applications is of narrative communication, creating stories of the past in a complete realistic ecosystem [28]. Interaction in the virtual world leads to story progression with the object changing or coming alive in the virtual world. This is often representative of an emphatic storyline, where the user progresses through the experience and develops an emotional connection to it.

Virtual worlds have applications beyond museums. They are being used in education, entertainment, and by experts to navigate new theories [28], [29]. Immersive applications provide opportunities of experiential learning that is difficult to achieve through traditional artefact viewing. People engage differently when presented with a new world of information. Some will explore the extents of the world, others will stop and look at everything they see, interacting with each object. The objects and areas of a world could be simply treated as visualisations or as hot spots to more information. However, where data is uncertain, it should be communicated in a transparent manner. This can be achieved by documenting all sources and material and allowing them to be accessed from within the virtual environment [30]. Having this transparency ensures that a coherent virtual world can be creatively developed around an artefact even when there is partial contextual data available.

III. Historical Research

The approach presented in this paper was applied to reconstructions of two Pictish sculpted stones: the St Madoes cross-slab and the Inchyra symbol stone. These were chosen because of their importance in the Perthshire region. The cross-slab is a largely intact monolithic sculpture of the eight century (Fig. 1), whilst the symbol stone is a possibly seventh century sculpture carved with Pictish symbols, to which at least three sets of ogham inscriptions have been added (Fig. 3). The sculptures are part of the collections of Perth Museum and Art Gallery. Since their re-discovery in the nineteenth and twentieth centuries respectively they have generally been treated as individual artefacts. In actuality, they come from the same temporal period and were found within the same landscape, something that is not immediately apparent due to the markedly changed landscape in which they once resided [31]. Hence, this was an opportunity to digitise and restore the collection of stones found here in order to present them to an audience who might not know of their link and the environment where they were found.

Fig. 1. St Madoes Cross-Slab (Front and Back).

Fig. 2. Restored St Madoes Cross-Slab (Front and Back).

A. Recreating a Pictish Colour Palette

A Pictish colour palette was composed in order to establish cohesiveness between the restored models and to ensure future reconstructions on other Pictish stones. The objective was to create a range of colours that would have been available to the Picts. Therefore, concurrent historical sources were investigated to make decisions on the colour selection. These sources included pigment remains on stone and illuminated manuscripts contemporary with the Pictish period.

Portable x-ray fluorescence and Raman spectroscopy techniques have previously been used to detect pigment chemical residue on Roman stonework [32]. The lead and iron deposits revealed a colour palette rich in reds and yellows, with traces of white lead. These colours have also been observed on post-Roman, Insular sculptures including the Anglo-Saxon

Fig. 3. Inchyra Symbol Stone (Front and Back).

Fig. 4. Restored Inchyra Symbol Stone (Front and Back).

Lichfield Angel. Here, the core colours used were mixed to create different hues, as well as adding black and white to create different shades [33]. Red pigment was found on sculpted interlace of the Pictish Portmahomack sculptures, while white, which was possibly used as a base layer, was found on the Goodlyburn cross-shaft[1] [20]. These findings reveal that reds, yellows, and white should be present in a Pictish colour palette. They also give an indication of which areas were painted and what effect could have been desired; most notably, using a white background to create contrast with the intricate designs.

More information was drawn from illuminated manuscripts, especially the Book of Kells (Fig. 5), created circa 800AD, and the Lindisfarne Gospels, created circa 715-720AD. These Insular artworks include intricate and colourful patterns in bright colours and a range which goes beyond red and yellow, to include blues and greens as well. These are the core hues that would have been available to Picts through natural minerals (red ochre or lead, yellow orpiment) and plants (woad blue). The colours could be mixed to create different hues and added to black charcoal or white lead to create different shades. A reconstruction of the Forteviot burial monument reproduced similar colours from the manuscripts (Fig. 6) [20]. From these colours, a 10-colour palette was created which is shown in Fig. 7. The 10 hues can be lightened or darkened and can capture accurate colours in any Pictish reconstructions.

B. Reconstructed Areas

With regards to the restoration of the stones, Inchyra has the most damage. The bottom wider part of the stone is broken off—destroying one of the fish symbols. This could be reconstructed by looking at the complete fish symbol incised on the other side. Most of the remaining restoration was in reconstructing pieces of the stone that had chipped off. Interestingly, two symbols on the Inchyra, on the side of the intact fish, were never finished by the creator [35]. These were only lightly incised in the final restored version and left unpainted to reflect their incompleteness. There is also some damage to the ogham inscriptions, mostly flaking. In order

[1]The white pigment on the Goodlyburn cross-shaft was identified by eye only. It is currently awaiting XRF confirmation.

Fig. 5. The Temptation of Christ, Book of Kells, folio 202v. [34].

Fig. 6. Forteviot burial monuments [20].

to not change the meaning of the inscription, no additional ogham lines were added, with the restoration only deepening their grooves.

The symbols on the St Madoes cross-slab have seen some erosion and damage and needed fine-tuning of their detail. The panels at the back of the stone are harder to make out but previous research had established what the symbols were originally [20]. The largest piece to be reconstructed was the top, where a pair of crouching lions were identified [31]. The reconstruction draws mostly from the lions carved on the Pictish sarcophagus found at St Andrews which was sculpted

Fig. 7. Pictish colour palette.

in the same period.

IV. Digitally Restoring Historical Artefacts

A workflow for artefact restoration was developed and applied to both stones. This is detailed below:

1) Carry out historical research and form a colour palette
2) Plan a colour scheme for each artefact
3) Import digitised 3D model
4) Sculpt missing sections
5) Restore selected areas by painting and refining detail
6) Export model for use in future applications

This workflow can be applied to any artefact, irrespective of its historical period. The concepts in the workflow can be adapted according to the artefact; for instance, if an artefact does not have missing fragments, that step can be skipped. The following section will describe some techniques that can be applied. It is not a comprehensive list, but the tools can be reused on any 3D model, as deemed fit.

The choice of software is an important one and for this project Adobe Mudbox and Blender were utilised and compared. Mudbox is a software dedicated to sculpting and painting a 3D mesh. It was appropriate for St Madoes as most of the restoration involved manipulating the existing mesh. This was possible using the sculpting tools which alter the model similarly to real-life sculpting. Since Inchyra required more extensive reconstruction, it was restored using Blender, which offers a suite of features that go beyond sculpting and editing. These include Boolean operators which seamlessly add new parts of the mesh. Moreover, Blender comes with multiple modifiers such as Remesh and Decimate. These tools help to fine-tune the final mesh, especially when new pieces have been added.

Blender was found to be the most appropriate program to synthesise 3D modelling techniques with the digitisation of an artefact to digitally restore historical artefacts. Working with a digital model which has been obtained through photogrammetry or other 3D scanning methods allows the final digital model to have realistic textures and accurate details. These would not be possible if a digital model is recreated from scratch.

A. Techniques Applied

Photogrammetrically scanned models, such as the two stones in this project create models with a high number of polygons. Moreover, the cloud points are often not uniform. This could be problematic when sculpting areas as the surfaces do not interact well with each other, creating vortex points or other errors. Therefore, some pre-processing is necessary to prepare the model for sculpting and painting. In the case of the Inchyra model, which was made up of many objects, the model was pre-processed by joining objects into one mesh and scaling to the correct real-life dimensions. This was followed by the Remesh modifier which created one mesh with orderly vertices and faces. This modifier can be controlled to reduce the number of faces without reducing the quality of the details. The mesh can also be Triangulated and Decimated to ensure smoother sculpting. The Remesh modifier can be reapplied to cohesively join additional fragments to the original mesh.

As discussed previously, there are several ways to reproduce missing areas in the 3D mesh. On St Madoes, this was the top part; on Inchyra, the biggest section was the bottom area, along with some smaller fragments that were dislodged at the time of discovery in the mid-1940s. For most of the smaller parts, using the in-built sculpting tools in Mudbox or Blender was sufficient to manipulate the vertices into shape. Bigger areas, such as the missing bottom of Inchyra, were done through copying similar areas of the stone. The new additions were scaled and shaped with the sculpting tools. Once complete, a Boolean Union operator merged the addition with the original mesh. This ensured any unused vertices were removed. The Remesh modifier could also be beneficial here to clean up the mesh before continuing to sculpt other details.

Once the structural changes have been made, the sculpting of details and painting can commence. Painting and refining should be done in a cyclical approach which ensures that areas of the model are viewed from every angle. Painting can be done on top of textures obtained through photogrammetry. Models which have been remeshed require a new UV projection to distribute the 3D vertex points onto the 2D texture.

B. Challenges

The main aim for a digitised cultural artefact is to preserve it for future generations and to catalogue it digitally. As such, a high level of detail which encompasses every aspect is required. However, for the model to be usable in other immersive applications, a balance must be reached between quality and size. This was a challenge while restoring. If the model has a small number of faces, it becomes difficult to sculpt details accurately. Higher-resolution meshes are required if the model is going to be displayed in life-size or bigger dimensions. On the other hand, subdividing the model excessively increases the number of faces and the size of the model. The final model becomes unusable in other applications due to a slow loading time. Computers or portable devices with less graphical power would struggle to smoothly interact with the model.

In Blender, file size can be reduced in multiple ways. The Decimate modifier reduces the number of faces with minimal shape changes by reducing unnecessary vertices in ‘flat’ areas where there is not much change in the topology. This is critical to ensure that detail is not lost. Blender also supports geometric mesh compression and can export the restored model in different formats to suite the intended use: FBX is a binary 3D format which can store multiple subdivision surfaces in less space and is ideal for use of the model in gaming engines; the glTF format, on the other hand, is optimised for real-time transmission, making it ideal for web-based applications. Because of its efficient size, it is widely used for VR and AR applications, as well as many digital heritage projects and public domain catalogues [36].

V. Immersive Learning Opportunities

The goal of restoring 3D artefacts is to bring them closer to the community. Immersive learning opportunities can be constructed through having accurate 3D digital replicas and restoring them in an authentic manner. Immersive applications provide an opportunity to learn about artefacts and their context. The restoration of these two stones has brought them together and they can be presented in meaningful ways. The following sections will detail two applications that have been developed which make use of the authentic restored reconstructions.

A. Interactive Configurator Tool

There is always room for interpretation when repainting historical artefacts, especially when little concrete evidence is present. This is something that ought to be communicated to the audience, without detaching from the learning experience. An online interpretation tool which enables the application of different colours on the artefact is effective. This is presented as part of a web interface that introduces the stones, their history, and context. The website is not overloaded with information to keep the content direct and meaningful. Additionally, it raises interest and allows the user to start forming their own thoughts and theories about how the stones might have looked like. A 3D visualisation is embedded which lets the user configure the different colours of the stone to reflect their own perceptions.

The configurator was built using the JavaScript library Three.js, ensuring it can work on any modern browser. It accepts 3D models in the GLTF format and can decode compressed models as well. The application builds the scene including the object, lights, and camera on an HTML canvas.

Once the model is loaded, three.js extensions provide orbit controls which allow panning, rotating, and zooming via mouse or touch. The user can then recolour the stone by selecting any part of the stone and choosing from the swatches of the provided Pictish colour palette. The configurator can be accessed through the interactive web interface at https://cineg.org/painting-the-picts/imagine/.

The 3D configurator is a valuable learning tool which emphasises the fact that the colouring of the stone is an exploratory task. This is shown to the viewer in a subtle manner which does not detract from the richness of the experience. Restricting the colour palette to the colours available to the Picts establishes their historical accuracy, whilst the freedom to create their own colour scheme certifies that the colour scheme of the model is not an exact replica.

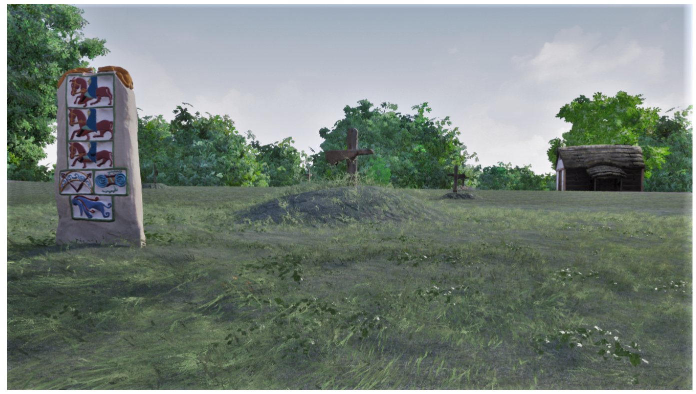

Fig. 8. Pictish environment showing the St Madoes Stone, cemetery, and Pictish church in the background.

B. Virtual Environment

Building a virtual environment of St Madoes in the early medieval period was an essential next step in disseminating an interpretation of the historical environmental context in which the Pictish stones had operated. The landscape has drastically changed due to a railway and motorway that presently pass through it. Archaeological, topographic, and onomastic evidence indicates that St Madoes was a significant place and had been since the Bronze Age, perhaps with some element of curated ritual continuity. Known features and finds include Bronze Age burial mounds and standing stones and a Roman coin hoard and brooch. The Inchyra stone was found adjacent to a Bronze Age burial mound and itself capped a burial. The St Madoes stone was found in the church burial ground, which when founded in the seventh century may have encroached upon the remnants of a prehistoric cemetery. From the churchyard came a further piece of Pictish sculpture currently lost and the recent find of another fragment of symbol stone indicates a concentration of Pictish sculpture in the area. This makes St Madoes/Inchyra a prime location for recreating a historical virtual landscape.

The Unreal Gaming Engine was used to create the virtual environment. The landscape maps were obtained from Digimap and used to create the digital landscape. The restored stones were imported and placed in their appropriate location. A medieval chapel was recreated. No reference remains have been found, but other historically contemporary buildings indicate that the chapel was most likely built of wood with a thatched roof. The model is relatively simple, without the precise detail that is present in the stones. The door and windows do not open, and the textures are two-dimensional. This highlights the fact that it is a creatively drawn reproduction reflective of its time, and not an authentic reconstruction based on direct evidence. Barrows were added to indicate the burial mounds and a cemetery built near the church and the cross-slab (Fig. 8). The scene was populated with typical flora and completed with indications of settlements.

The virtual environment provides opportunities to walk around the scene with a first-person perspective. As a learning environment, users can freely explore the environment, intrinsically finding answers to their questions about the stones. As this can be applied to any artefact, users can learn about the people who built and used historical artefacts through seeing and interacting with the worlds they lived in, and not just through reading information. Parallels and contrasts between the current environment and the historical one can easily be drawn which assist in the understanding of this cultural landscape and its evolution.

VI. Analysis and Future Development

The work presented here was shared with several history and museum professionals who provided feedback. The debate of whether the Picts painted on a white base layer or directly onto the stone was prominent. The configurator tool was modified to reflect this by including a choice of both options. The consulted experts were satisfied with how the surfaces were digitally restored during the process of sculpting on the 3D model. There were positive comments on how the colour interplays with reliefs in the stones, bringing out unseen detail. Further changes to the virtual environment, such as depicting moving light, could add insight into the appearance of the stones at different times in the day.

The virtual scene can be further evolved into an educational game by providing a narrative structure and creating goals or other game mechanics. This could be extended to a multi-player platform which inspires collaboration and social interaction, providing new learning experiences. Characters can be added which add a level of personalisation to the game by exploring the world differently. Additional non-player characters can be included in the scene which help to pass on information.

The restored digital artefacts still have a place in the museum: the configurator for each stone can be used in a tangible user interface alongside the real-life stones to promote further thought and exploration of how the stones looked like; the colour scheme can be projected onto the stones to simulate how the colours were applied; augmented reality applications can be created to access and view the restored version whilst looking at the physical artefact.

VII. Conclusion

This paper has made several contributions which encourage the effective use of digitised historical artefacts. On a conceptual level, a workflow has been developed which synthesises 3D modelling techniques with digitised artefacts. This can be used to authentically restore artefacts in a non-invasive digital manner. This has been applied to the St Madoes and Inchyra Pictish stones. In the process, a Pictish colour palette was composed which can be applied to any future colourisation of Pictish stones. A colour configurator tool has been developed which boosts interpretation and the stones were placed in a virtual environment, representative of their context. The restored digital models have thus been utilised to create immersive and exploratory applications which aid in the understanding of the stones' original landscape. This is crucial in educational contexts, where a holistic understanding of the contexts of artefacts can be achieved through interaction with such historically accurate reproductions.

References

[1] J. Hindmarch, M. Terras, and S. Robson, "The cultural heritage object in the age of 3d digital reproduction," *The Routledge International Handbook of New Digital Practices in Galleries, Libraries, Archives, Museums and Heritage Sites*, pp. 243–256, 2019.

[2] A. Jeffs, F. Insh, E. H. Matthes, T. Flynn, D. Pett, T. Ayers *et al.*, "Disciplining the digital: Virtual 3d reproduction, pilgrim badges, and the stuff of art history," *British Art Studies*, no. 6, 2017.

[3] J. McCarthy, E. Sebo, B. Wilkinson, and F. Sheehan, "Open workflows for polychromatic reconstruction of historical sculptural monuments in 3d," *Journal on Computing and Cultural Heritage (JOCCH)*, vol. 13, no. 3, pp. 1–16, 2020.

[4] J. McCarthy, "Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement," *Journal of Archaeological Science*, vol. 43, pp. 175–185, 2014.

[5] J.-B. Barreau, Y. Bernard, R. Gaugne, G. Le Cloirec, and V. Gouranton, "The west digital conservatory of archaeological heritage project," in *2013 Digital Heritage International Congress (DigitalHeritage)*, vol. 1. IEEE, 2013, pp. 547–554.

[6] P. Sapirstein, "Accurate measurement with photogrammetry at large sites," *Journal of Archaeological Science*, vol. 66, pp. 137–145, 2016.

[7] G. Bogdanova, T. Todorov, and N. Noev, "Digitization and 3d scanning of historical artifacts," *Digital Presentation and Preservation of Cultural and Scientific Heritage*, pp. 133–138, 2013.

[8] A. K. Shurik, "Comparing 3 techniques for 3d digitizing small artifacts photogrammetry laser scanning 3d structured light scanning," in *Presentation at the AAA in San Jose, CA.*, 11 2018.

[9] R. M. Ruiz, M. T. M. Torres, and P. S. Allegue, "Comparative analysis between the main 3d scanning techniques: Photogrammetry, terrestrial laser scanner, and structured light scanner in religious imagery: The case of the holy christ of the blood," *ACM Journal on Computing and Cultural Heritage (JOCCH)*, vol. 15, no. 1, pp. 1–23, 2021.

[10] A. Mathys, J. Brecko, and P. Semal, "Comparing 3d digitizing technologies: what are the differences?" in *2013 Digital Heritage International Congress (DigitalHeritage)*, vol. 1. IEEE, 2013, pp. 201–204.

[11] H. England, "3d laser scanning for heritage," Historic England, Tech. Rep. 3, 02 2018. [Online]. Available: https://historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage/heag155-3d-laser-scanning/

[12] M. Altaweel, "The earth archive project and 3d mapping the earth," https://www.gislounge.com/the-earth-archive-project-and-3d-mapping-the-earth/, 06 2020, accessed: 2022-01-27.

[13] D. Pritchard, J. Sperner, S. Hoepner, and R. Tenschert, "Terrestrial laser scanning for heritage conservation: the cologne cathedral documentation project." *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, vol. 4, 2017.

[14] Y. Praticò, J. Ochsendorf, S. Holzer, and R. J. Flatt, "Post-fire restoration of historic buildings and implications for notre-dame de paris," *Nature Materials*, vol. 19, no. 8, pp. 817–820, 2020.

[15] A. Pesci, E. Bonali, C. Galli, and E. Boschi, "Laser scanning and digital imaging for the investigation of an ancient building: Palazzo d'accursio study case (bologna, italy)," *Journal of Cultural Heritage*, vol. 13, no. 2, pp. 215–220, 2012.

[16] A. Costanzo, M. Minasi, G. Casula, M. Musacchio, and M. F. Buongiorno, "Combined use of terrestrial laser scanning and ir thermography applied to a historical building," *Sensors*, vol. 15, no. 1, pp. 194–213, 2015.

[17] J. J. Emmitt, T. Mackrell, and J. Armstrong, "Digital modelling in museum and private collections: A case study on early italic armour," *Journal of Computer Applications in Archaeology*, vol. 4, no. 1, 2021.

[18] Y. H. Jo, S. Hong, S. Y. Jo, and Y. M. Kwon, "Noncontact restoration of missing parts of stone buddha statue based on three-dimensional virtual modeling and assembly simulation," *Heritage Science*, vol. 8, no. 1, pp. 1–12, 2020.

[19] H. Denard, "A new introduction to the london charter," *Paradata and transparency in virtual heritage*, pp. 57–71, 2012.

[20] M. A. Hall, "Show and tell: Re-articulating the monumentality of power, or picts in the museum," *Peopling Insular Art: Practice, Performance, Perception*, p. 207, 2020.

[21] J. Kesik, J. Montusiewicz, and R. Kayumov, "An approach to computer-aided reconstruction of museum exhibits," *Advances in Science and Technology. Research Journal*, vol. 11, no. 2, 2017.

[22] Y. Yu, K. Zhou, D. Xu, X. Shi, H. Bao, B. Guo, and H.-Y. Shum, "Mesh editing with poisson-based gradient field manipulation," in *ACM SIGGRAPH 2004 Papers*, 2004, pp. 644–651.

[23] H. Biermann, I. Martin, F. Bernardini, and D. Zorin, "Cut-and-paste editing of multiresolution surfaces," *ACM Transactions on Graphics (TOG)*, vol. 21, no. 3, pp. 312–321, 2002.

[24] S. Lautenschlager, "Reconstructing the past: methods and techniques for the digital restoration of fossils," *Royal Society Open Science*, vol. 3, no. 10, p. 160342, 2016.

[25] E. Nofal, M. Reffat, and A. Vande Moere, "Phygital heritage: An approach for heritage communication," in *Immersive Learning Research Network Conference*. Verlag der Technischen Universität Graz; Graz, Austria, 2017, pp. 220–229.

[26] C. J. Davies, A. Miller, and C. Allison, "A view from the hill: Where cross reality meets virtual worlds," in *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology*, ser. VRST '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 213. [Online]. Available: https://doi.org/10.1145/2671015.2671138

[27] C. Davies, A. Miller, and R. Fawcett, "Mobile onsite exploration of parallel realities with oculus rift," in *2015 Digital Heritage*, vol. 1, 2015, pp. 301–304. [Online]. Available: https://ieeexplore.ieee.org/document/7413887

[28] I. Cerato and S. Pescarin, *Reconstructing Past Landscapes for Virtual Museums*. Springer International Publishing, 2013, pp. 285–296. [Online]. Available: https://doi.org/10.1007/978-3-319-01784-6_17

[29] A. H. D. Miller, C. Allison, and K. M. Getchell, "Open virtual worlds: A serious platform for experiential and game based learning," *Proceedings of MCIS 2012*, 2012.

[30] P. Fleury and S. Madeleine, "Reviving ancient rome: virtual reality at the service of cultural heritage," in *Euro-Mediterranean Conference*. Springer, 2012, pp. 159–169.

[31] M. A. Hall, "Three stones, one landscape, many stories: cultural biography and the early medieval sculptures of inchyra and st madoes, carse of gowrie, perthshire, scotland," in *Narrating Objects, Collecting Stories*. Routledge, 2012, pp. 101–118.

[32] L. Campbell, "Polychromy on the antonine wall distance sculptures: non-destructive identification of pigments on roman reliefs," *Britannia*, vol. 51, pp. 175–201, 2020.

[33] A. Geary and E. Howe, "Three-dimensional documentation and virtual restoration of the lichfield angel," *Journal of the Institute of Conservation*, vol. 32, no. 2, pp. 165–179, 2009.

[34] Anon., "Book of kells. ie tcd ms 58," https://digitalcollections.tcd.ie/concern/works/hm50tr726, accessed: 2022-01-27.

[35] R. Stevenson, "The inchyra stone and some other unpublished early christian monuments," in *Proceedings of the Society of Antiquaries of Scotland*, vol. 92, 1961, pp. 33–55.

[36] R. Bradshaw and A. Crabb, "Khronos and smithsonian collaborate to diffuse knowledge for education, research, and creative use," 02 2020, accessed: 2022-01-28. [Online]. Available: https://www.khronos.org/news/press/khronos-smithsonian-collaborate-to-diffuse-knowledge-for-education-research-and-creative-use